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Naval Warfare Research Center

Final Report

NAVAL APPLICATIONS OF MAN-IN-THE-SEA CONCEPTS

By: A. BIEN and P. J. McDONOUGH

Prepared for:

THE OFFICE OF NAVAL RESEARCH
NAVAL ANALYSIS PROGRAMS
DEPARTMENT OF THE NAVY
ARLINGTON, VIRGINIA 22217

CONTRACT N00014-68-A-0243-0002
TASK NR 274-008-12

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SRI Project 7000-212

Approved by:

LAWRENCE J. LOW, *Director*
Naval Warfare Research Center

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NWRC 7000-212-1

ABSTRACT

Naval undersea missions and operations in the 1975-85 time frame that require the use of MAN-IN-THE-SEA systems are delineated. The MAN-IN-THE-SEA system is broadly defined in this study to include all undersea systems requiring man's exposure to the ambient ocean pressure. MAN-IN-THE-SEA missions and operations within the overall spectrum of naval undersea missions and operations are isolated on the basis of system investment and operating costs. It is demonstrated that MAN-IN-THE-SEA has a definite role in accomplishing future naval undersea missions and operations. MAN-IN-THE-SEA systems offer both functional and cost advantages over alternative systems in the performance of a number of naval missions in the shallower depth regions (less than 150 feet). In depths greater than 150 feet, MAN-IN-THE-SEA systems offer functional advantages at comparable costs to alternative systems in the performance of some naval missions.

PREFACE

This study of the naval application of MAN-IN-THE-SEA concepts in the 1975-85 time frame was sponsored by the Naval Analysis Programs Group, Mr. J. R. Marvin, Director, in the Office of Naval Research. Mr. B. L. Friedman was the ONR Project Scientific Officer. The fundamental objectives of the study were to identify the potential contributions of MAN-IN-THE-SEA capabilities to the accomplishment of naval missions. The results of the study are to provide guidelines for the structuring of a long range MAN-IN-THE-SEA research program.

The research effort was performed by the Naval Warfare Research Center of Stanford Research Institute. Mr. A. Bien of NWRC was the principal investigator. Mr. P. J. McDonough of the Santa Barbara Analysis and Planning Corporation was the principal subcontractor.

ACKNOWLEDGMENTS

In addition to the authors, contributions to this research effort were made by the following SRI personnel: Mr. A. M. Hudson, research engineer; Mr. S. Bloomfield, operations analyst; Mr. S. E. Stuntz, research psychologist. Miss J. Marston, Mrs. T. Silvia, and Mrs. M. Killam provided invaluable help in the preparation of this report.

A study such as the one reported on here is made possible by the cooperative support of the military departments and their contractors. Cognizant personnel of the following organizations provided valuable guidance and information essential to the conduct of the study:

Office of Naval Research
Engineering Psychology Branch
Washington, D. C.

Deep Submergence Systems Project Office
Bethesda, Maryland

Office of Chief of Naval Operations
Ocean Engineering Planning Group
Washington, D.C.

Experimental Diving Unit
Washington, D.C.

U.S. Navy Mine Defense Laboratory
Panama City, Florida

U.S. Navy Submarine Medical Center
Medical Research Laboratory
New London, Connecticut

Office of the Supervisor of Salvage
Washington, D.C.

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U.S. Naval Undersea Research and Development Center
San Diego, California

U.S. Naval Weapons Center
China Lake, California

Naval Facilities Engineering Command
Washington, D.C.

Naval Civil Engineering Laboratory
Port Hueneme, California

Northrop, Nortronics Division
Palos Verdes Peninsula, California

North American Rockwell
Ocean Systems Operation
Compton, California

General Dynamics
Electric Boat Division
Groton, Connecticut

Whittenburg, Vaughan, Incorporated
Fairfax, Virginia

Oceanic Institute
Makapuu Point
Waimanalo, Hawaii

STUDY SUMMARY

NAVAL APPLICATIONS OF MAN-IN-THE-SEA CONCEPTS

BACKGROUND

MAN-IN-THE-SEA concepts are defined broadly as those underwater systems where man is exposed to the ambient pressure in the ocean environment. This approach contrasts with those underwater systems in which man is protected from the ambient pressure by: (1) placing him in the protective shell or a pressure vessel, or (2) locating him on the sea's surface and having him remotely operate underwater equipments.

In recent years significant advances in the capabilities of MAN-IN-THE-SEA concepts have been realized. These advances, resulting principally from the development of saturation diving techniques, are reflected in the extended depth and time man is able to venture into the sea. The U.S. Navy, recognizing the possible military potentials offered by man's increasing undersea capabilities, is supporting a MAN-IN-THE-SEA program. This program is directed toward developing man's ability to accomplish useful work down to the depth of the continental shelf and determining man's ultimate depth-time limits in the ambient undersea environment.

In light of the demonstrated and promising capabilities of MAN-IN-THE-SEA concepts and the recognized need for expanded research and development efforts to extend man's ability to live and work under the sea, the U.S. Navy must establish its long range goals and objectives for the exploitation of these concepts. An analysis of the potential contributions of MAN-IN-THE-SEA capabilities to the accomplishment of naval missions was needed to provide guidelines for the structuring of a long range MAN-IN-THE-SEA program.

The primary objective of this research effort, sponsored by the Office of Naval Research, was to identify and establish how, where, when, and why MAN-IN-THE-SEA concepts contribute to the accomplishment of naval missions.

STUDY RESULTS

Missions, Operations, and Tasks

A spectrum of naval undersea missions and operations was identified through a comprehensive review of total naval requirements in support of current and future national objectives. This type of review was considered a basic prerequisite for all naval supported, mission oriented studies. The method used to identify naval undersea missions and operations was selected because it could provide requirement definitions that are related to, and supported by, current naval research planning procedures. As a result of this approach, a more complete and systematic overview of naval undersea operational requirements was achieved than was previously available.

Since the utility of a specific undersea system, or a combination of systems, in accomplishing the undersea missions and operations is dependent primarily upon the tasks associated with each mission and operation, a critical step in the determination of the application of the MAN-IN-THE-SEA concept is the identification of undersea tasks and their association with missions and operations.

The defined naval undersea missions and operations, and the associated generalized tasks, are shown in Table S-1. Supporting data for the defined naval undersea missions and operations are presented in a classified addendum to this report.

Table S-1

NAVAL UNDERSEA MISSIONS, OPERATIONS, AND ASSOCIATED TASKS

Generalized Task Spectrum / * Undersea Missions and Operations	Class I	Class II			Class III			Class IV			
	Search/Locate	Observe	Survey	Measure	Pickup	Transport	Place	Attach {Drill, Bolt, Rivet, Connect/hookup, Clamp}	Detach {Drill, Burn, Saw, Hammer, Chip, Scrape, Wipe}	Apply (Fill) {Hose, Paint}	Excavate {Core, Dredge, Trench, Tunnel}
Surveillance											
Landing beach area		X	X		X	X	X				
Enemy harbor		X	X		X	X	X				
U.S. harbor protection		X	X		X	X	X				
Inshore USW		X	X		X	X	X				
USW all ranges & depths		X	X		X	X	X				
Reconnaissance											
Beach area	X		X	X	X	X	X				
Enemy harbor	X		X	X	X	X	X				
Mining environment	X		X	X	X	X	X				
Mining											
Mine hunting and countermeasures	X		X	X		X	X				
Mine plants						X	X				
Disarm mine								X	X		X
Interrogate mine fields	X	X	X								
Navigation Surveys											
Recovery											
Small object	X		X		X	X					
• Torpedoes	X		X		X	X					
• Nuclear weapons	X		X		X	X					
• Space hardware	X		X		X	X					
Large object	X		X	X	X	X	X	X	X	X	X
Facility Installations											
Sonar array (align & repair)			X	X	X	X	X	X	X	X	
Bottom mounted ULM			X	X	X	X	X	X	X	X	X
Navigation markers			X	X	X	X	X				
Cable laying & inspection			X	X	X	X	X	X			
General construction			X	X	X	X	X	X	X	X	X
Salvage											
Ships	X	X	X	X	X	X	X	X	X	X	X
Aircraft	X	X	X	X	X	X	X	X	X	X	X
Repairs											
In port (wet dock)								X	X	X	
Underway								X	X	X	
Support											
Oceanographic data		X	X	X	X	X	X	X	X	X	X
Sub rescue personnel	X	X	X			X	X	X	X	X	X
Underwater logistics		X			X	X	X	X	X		
Habitat Development											

■ Undersea mission areas   [X] Undersea operations within the broad mission areas

*Supporting data for undersea mission and operations are presented in a classified addendum to this report:

A. Bien and P.J. McDonough; "Addendum to Naval Applications of MAN-IN-THE-SEA CONCEPTS--Mission Definition (U)"; SRI Research Memorandum NWRC RM-50, Contract No. N00014-68-A-0243; Stanford Research Institute, Menlo Park, California; December 1968 (SECRET)

Comparative Analysis Results

The procedure used for isolating MAN-IN-THE-SEA missions and operations within the spectrum of naval undersea missions and operations was: (1) to compare the functional capabilities of MAN-IN-THE-SEA systems with those systems that do not require man's exposure to the ambient ocean environment (alternatives to the MAN-IN-THE-SEA systems), and (2) to compare the costs of using MAN-IN-THE-SEA systems with the alternative systems. Thus, the MAN-IN-THE-SEA system application study reported here is unique in that the need for MAN-IN-THE-SEA concepts to accomplish particular naval missions and operations was not an initial study assumption.

The criteria used in defining the functional performance requirements related to the undersea naval missions and operations and the functional performance capabilities of alternative undersea systems were:

- Depth capability
- Time capability
- Mobility capability
- Load carrying capability
- Maneuvering Capability
- Manipulative capability
- Sensory capability
- Cognitive skills
- Hardness
- Covertness.

Table S-2 summarizes the functional comparison results and indicates the performance areas where: (1) MAN-IN-THE-SEA systems possess unique capabilities, (2) MAN-IN-THE-SEA and alternative systems have comparable capabilities, and (3) alternative systems have unique capabilities.

Table S-2

SUMMARY OF THE RESULTS OF FUNCTIONAL CAPABILITIES COMPARISON

FUNCTIONAL CAPABILITIES	MAN-IN-THE-SEA Unique Capabilities	MAN-IN-THE-SEA and Alternatives Comparable	Alternatives Unique Capabilities
Mobility			■
• Speed			■
• Range			■
Load Carrying			■
• Object size			■
• Object weight			■
Maneuverability	■		
• Access limit	■		
• Degrees freedom	■		
Manipulation		■	
• Minimum skill		■	
• Moderate skill	■		
• Complex skill	■		
Sensing	■	■	■
• Visual		■	
• Acoustic			■
• Electromagnetic			■
• Magnetic			■
• Electric			■
• Tactile	■		
Cognition		■	
• On-scene assess.		■	
Hardness			■
• Mechanical			■
• Radiation			■
• Temperature			■
• Marine life			■
Covertness	■		
• Visual	■		
• Acoustic	■		
• Electromagnetic	■		
• Magnetic	■		
• Electrical	■		
• Pressure	■		

The comparative analysis of the functional capabilities of MAN-IN-THE-SEA systems versus the alternatives, based on the foregoing criteria, indicated that the unshielded man is unique only in the following sense:

1. He offers a significant advantage in maneuverability because of his compactness, agility, and physical flexibility.
2. He offers a significant advantage in manipulative capability for tasks that require a high degree of finger dexterity.
3. He offers extended sensory capability because of his tactile senses. These senses enhance man's manipulative capability, especially in extremely turbid water.
4. He offers some degree of covertness in certain operational environments.

The criteria used in making the cost comparison are the initial systems investment cost and the operating costs of accomplishing a specific mission or operation, e.g., small object recovery, aircraft salvage, or undersea facilities construction. Since MAN-IN-THE-SEA systems configurations and operational modes differ for a particular depth regime, the cost comparisons are made in relation to four depth bands. These bands are 0-30 ft, 30-150 ft, 150-300 ft, and 300 ft and greater. It is recognized that the boundaries of each depth band are not clear-cut and that there exists a certain amount of overlap.

Table S-3 summarizes the cost comparison results and indicates the regions where: (1) MAN-IN-THE-SEA systems have a cost advantage, (2) MAN-IN-THE-SEA systems and alternatives have comparable costs, and (3) alternative systems have a cost advantage. The five missions/operations selected for comparison were: (1) small object recovery, (2) aircraft salvage, (3) ship salvage, (4) simple undersea construction, and (5) undersea facilities construction. These missions-operations represent a wide range of demands in the undersea task to be performed,

Table S-3

SUMMARY OF THE RESULTS OF COST COMPARISONS

	Investment Costs				Operating Costs			
	0-30 ft	30-150 ft	150-300 ft	300 ft →	0-30 ft	30-150 ft	150-300 ft	300 ft →
MAN-IN-THE-SEA Cost Advantage	1 2 3 4 5	1 2 3 4 5			1 2 3 4 5	1 2 3 4 5	3 5	2 3 5
MAN-IN-THE-SEA and Alternatives Costs Comparable				1 2 3 4 5			1 2 4	1 4
Alternatives Cost Advantage			2 3 4 5					

1. Small object recovery
2. Aircraft salvage
3. Ship salvage
4. Simple undersea construction
5. Undersea facilities construction

e.g., from minimal manipulative work requirements to highly complex manipulative work requirements. A wide range of total operational time is also represented, e.g., from 2 days in small object recovery to 60 days in ship salvage operations. Some specific observations of the cost comparison results are the following:

1. A dominant investment and operating cost component for MAN-IN-THE-SEA and alternative systems is the cost of the support platforms.
2. For operating depths up to about 150 ft MAN-IN-THE-SEA systems <u>always</u> have an investment and operating cost advantage over the alternative systems.
3. The investment cost advantage of alternatives to MAN-IN-THE-SEA in the depth region between 150-300 ft is achieved by the use of the articulated diving dress. Since 300 ft is technically a maximum projected depth capability for the diving dress, MAN-IN-THE-SEA may also have cost advantage in the 150- 300-ft depth region if the diving dress cannot achieve the projected depth.
4. MAN-IN-THE-SEA systems investment costs for depth region beyond 300 ft are comparable to the alternative systems costs.
5. MAN-IN-THE-SEA systems have an operating cost advantage over the alternative systems for mission/operations that require large amounts of manipulative work.
6. MAN-IN-THE-SEA systems operating costs are comparable to the alternative systems cost where there is only a moderate amount of manipulative work.

<u>Mission and Operation Allocation Criteria</u>

The two principal criteria that determine the allocation of naval undersea missions to MAN-IN-THE-SEA systems or the alternative systems are: (1) the mission survivability of system, and (2) the cost of the system.

Since in the shallower depth region (0-150 ft) MAN-IN-THE-SEA systems have a significant cost advantage over the alternatives, the allocation of missions to systems other than MAN-IN-THE-SEA systems must consider the advantage of achieving survivability through hardened systems rather than through covert operations.

In the depth regions beyond 150 ft, where MAN-IN-THE-SEA systems costs are comparable to the alternatives, the choice is less difficult since the use of hardened systems need not be bought at increased costs.

The role of MAN-IN-THE-SEA systems in satisfying naval undersea missions and operations based upon the consideration of the systems mission survivability through the use of covert or hardened system operations is summarized in Table S-4.

As shown in Table S-4, Condition I identifies those undersea missions and operations that MAN-IN-THE-SEA systems can best satisfy if survivability is to be achieved through covert operation.

Condition II identifies those underseas missions and operations that MAN-IN-THE-SEA systems can best satisfy if survivability is to be achieved through hardened systems.

Condition II' extends Condition II where consideration is given to the design of undersea facilities to minimize the constraints imposed by the limitations of mechanical manipulators. This consideration is included to demonstrate the difference between the accomplishment of an operation that is under the control of the designer and one that is not. For example, ship salvage operation is a nondesignable job that requires the full flexibility of man to handle, whereas, undersea structures can be designed to eliminate the need for MAN-IN-THE-SEA systems.

Table S-4

SUMMARY OF THE ROLE OF MAN-IN-THE-SEA SYSTEMS

Functional Operations / Mission Conditions	Condition I: Mission Emphasis on the Use of Covert Operations	Condition II: Mission Emphasis on the Use of Hardened Systems	Condition III: And the Advanced Design of Underseas Structures
Surveillance	■		
● Landing beach area	■		
● Enemy harbor	■		
● U.S. harbor protection			
● Inshore USW	■		
● USW all ranges and depths			
Reconnaissance	■		
● Beach area	■		
● Enemy harbor	■		
● Mining environment	■		
Mining	■	■	■
● Mine hunting and countermeasures	■		
● Mine plants			
● Disarm mine	■	■	■
● Interrogate mine fields	■		
Navigation Surveys			
Recovery	■	■	■
● Small object	■		
Torpedoes	■		
Nuclear weapon	■		
Space hardware	■		
● Large object	■	■	■
Facility Installations	■	■	
● Sonar array (align and repair)	■	■	
● Bottom mounted ULM	■	■	
● Navigation markers			
● Cable laying and inspection	■	■	
● General construction			
● Foundation and bottom	■	■	■
Salvage	■	■	■
● Ship	■	■	■
● Aircraft	■	■	■
Repairs	■	■	■
● In port (wet dock)	■	■	■
● Underway	■	■	■
Support	■	■	■
● Oceanographic data			
● Sub rescue personnel	■	■	
● Underwater logistics	■	■	■
● Habitat Development	■	■	

■ MAN-IN-THE-SEA functional application area

CONCLUSIONS

The study results presented in the preceding section demonstrate that MAN-IN-THE-SEA systems have a definite role in the conduct of future naval undersea missions and operations. The advantages of MAN-IN-THE-SEA systems in the depth region of 0-150 ft is quite clear. This conclusion can be accepted with reasonable confidence even though the study relied heavily upon subjective estimates of systems' functional capabilities and gross estimates of systems' costs.

The advantages of MAN-IN-THE-SEA systems in the depth region beyond 150 ft is not as clear-cut. The analysis has shown, in general, a comparable cost for MAN-IN-THE-SEA systems versus the alternatives. However, this result is highly sensitive to the accuracy of the estimates of the functional capabilities of MAN-IN-THE-SEA systems and alternatives. The subjective estimates of the functional capabilities of undersea work systems, necessitated by the lack of quantitative measurements, makes the comparison results less reliable. While MAN-IN-THE-SEA systems show slight advantage over alternative systems in this present analysis, there is a good chance that future developments of alternatives to MAN-IN-THE-SEA systems may reverse this. The above conclusion was arrived at through two basic observations:

1. The unique capabilities of MAN-IN-THE-SEA systems, maneuverability, tactile sensing, and manipulative capabilities are being erroded by undersea vehicle technology developments in the form of advanced sensor, control, and mechanical manipulator systems

2. Undersea systems that can be designed (e.g., surveillance devices, missile sites, facilities) are being configured to minimize the need for complex manipulative work. In certain cases major effort has been devoted to design undersea systems that match the limited capabilities of current manipulator equipped vehicles.

It is essential, therefore, that the contributions of MAN-IN-THE-SEA systems versus alternative systems in the conduct of naval undersea missions and operations be continually reassessed in light of the advancing technological developments. A critical facet of this reassessment is the determination of quantitative measures of the functional capabilities of MAN-IN-THE-SEA systems versus the alternatives. In terms of the performance criteria developed in this study the manipulative capability of MAN-IN-THE-SEA systems compared with alternative systems is one of the most important measures that need to be quantified. Detailed descriptions of other performance measures are presented in Section V of this report.

CONTENTS

CONTENTS (Continued)

CONTENTS (Concluded)

ILLUSTRATIONS

ILLUSTRATIONS (Continued)

ILLUSTRATIONS (Concluded

TABLES

TABLES (Continued)

TABLES (Continued)

TABLES (Concluded)

I INTRODUCTION

This report consolidates the results of a two-phase research effort that examines the potential contributions of MAN-IN-THE-SEA systems to the accomplishment of naval missions.

The two-phase study approach that was adopted is outlined in Fig. I-1. The essential tasks were to: (1) identify Navy mission areas, related functions and tasks, and required mission-performance capabilities; (2) define the performance capabilities of MAN-IN-THE-SEA systems and alternatives to MAN-IN-THE-SEA systems; (3) conduct a comparative analysis of the functional capabilities of MAN-IN-THE-SEA systems versus the alternatives; and (4) conduct a comparative analysis of the costs of MAN-IN-THE-SEA systems versus the alternatives.

The substance of the study approach lies in Tasks 3 and 4, viz., the comparative analysis of MAN-IN-THE-SEA systems versus the alternatives. The major difficulty in establishing valid missions requiring the use of MAN-IN-THE-SEA concepts is that there may be other means that could achieve the same missions. These alternatives might be tethered remote controlled vehicles equipped with acoustic and visual sensors and manipulators, or manned manipulator equipped free swimming vehicles. The major advantage of these alternatives is that man is not directly exposed to the extremely hostile ambient underwater environment. The objectives of the study's first phase were to identify those underwater tasks that require the capabilities of a man working in direct contact with his environment and relate those tasks to Navy underseas missions. In essence, the study sought answers to the following interrelated questions:

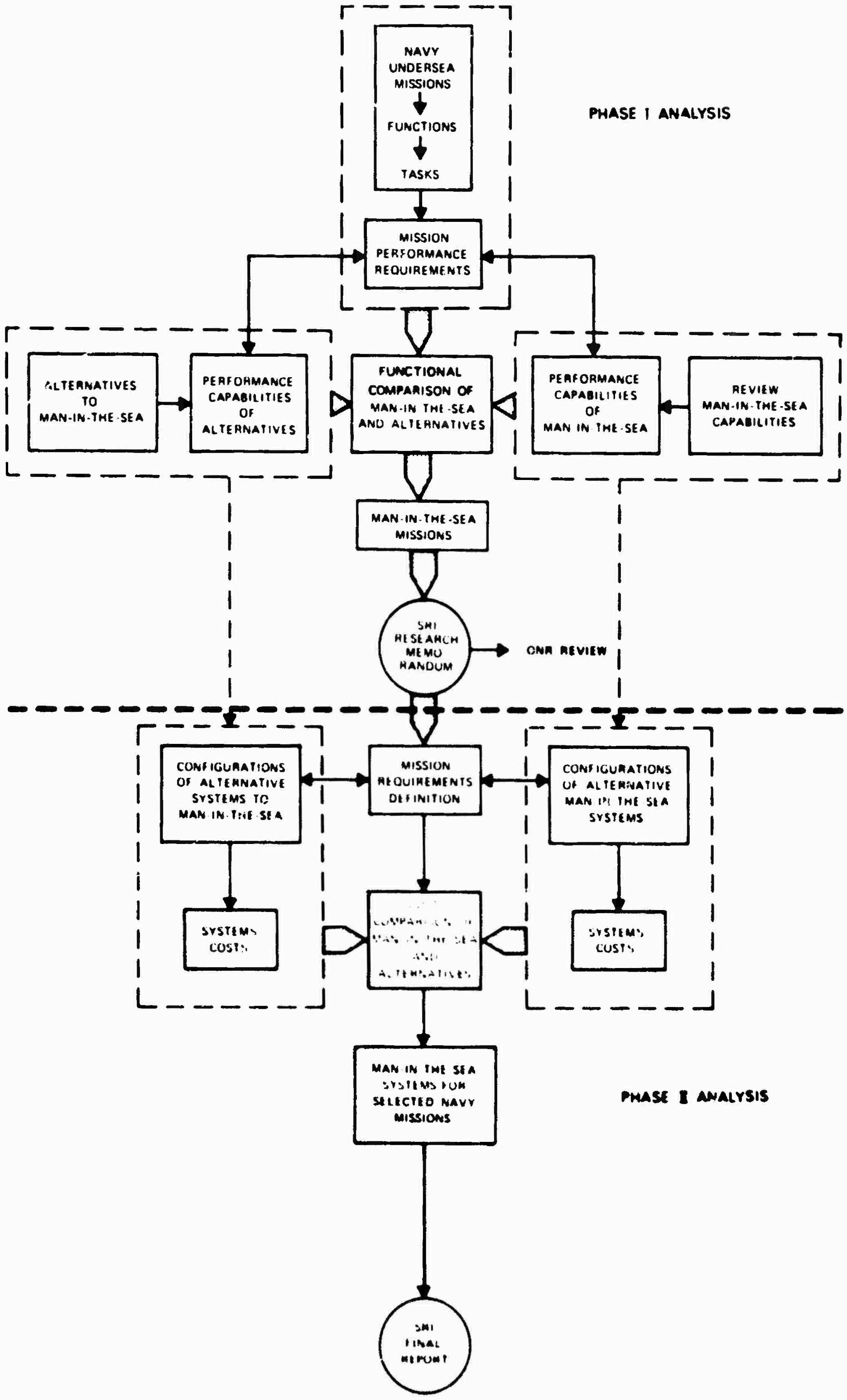

FIGURE I-1 WORK FLOW DIAGRAM OF THE STUDY OF NAVAL APPLICATIONS OF MAN-IN-THE-SEA CONCEPTS

- What unique capabilities for accomplishing specific underwater tasks does an unshielded man have?
- Which Navy undersea missions have essential tasks requiring those unique capabilities?

The spectrum of Navy undersea missions and operations is identified in Section II. The tasks related to each mission and operation are identified in Section III. MAN-IN-THE-SEA systems options, together with alternative systems options, are delineated and described in Section IV. Based upon a defined set of performance criteria, the functional capabilities of MAN-IN-THE-SEA systems and alternative systems are compared (Section V). The investment and operating costs of performing specific undersea missions and operations are compared in Section VI. Detailed task analyses for selected Navy missions are provided in Appendix A. Reviews of the fundamentals and performance capabilities of MAN-IN-THE-SEA systems and alternative systems are provided in Appendixes B and C. Appendix D contains summary of cost data used in cost comparisons. A comprehensive bibliography of all aspects of MAN-IN-THE-SEA systems and operations is given in Appendix E. <u>Supporting data for naval undersea missions are presented in a classified addendum to this report (see Table S-1)</u>.

II NAVAL UNDERSEA MISSIONS AND OPERATIONS

A. General

The spectrum of naval undersea missions and operations was developed through the use of three principal sources. These sources are:

1. Comprehensive review of documented naval military requirements in support of current and projected future national objectives.
2. Consolidation of future undersea mission requirements as postulated by: (1) naval and other DOD agencies, (2) U.S. Naval Laboratory personnel engaged in undersea systems development, and (3) contractors to DOD and Naval Laboratories.
3. Postulation of advanced undersea missions by the study team.

It became quite apparent, after completion of the review of sources 1 and 2 described above, that very few new undersea missions exist. Therefore, it was considered that postulation of advanced mission through the generally accepted process of future threat and counterthreat analyses would be redundant and not warranted by this study. The naval undersea missions and operations identified in this study are tailored to provide requirement definitions that are related to, and supported by, current Navy research planning procedures. This approach provided a more complete and systematic overview of naval undersea operational requirements than was previously available.

B. Sources of Missions and Operations Requirements

The method used to define naval undersea missions and operations is outlined in Fig. II-1. First, a thorough review was made of current naval warfare operations and applications as described in the NWPs and NWIPs. This review was accomplished, using the NWPs and NWIPs listed in Table II-1. Only those documents from the official list of tactical

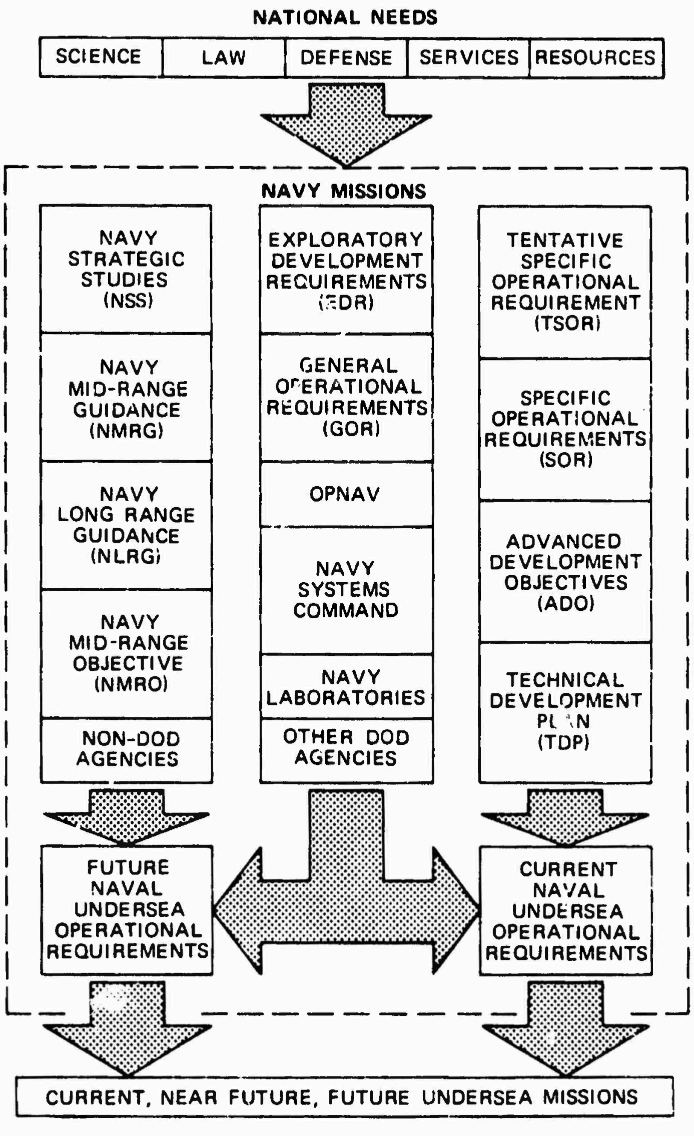

FIGURE II-1 SUMMARY OF APPROACH TO THE IDENTIFICATION OF NAVY UNDERSEA MISSIONS

Table II-1

TACTICAL PUBLICATIONS STATUS REPORTS

Short Title	Long Title	Classi-fication	Last Change
NWP 11-A	Naval Operational Planning	C	2 12 66
NWP 22-A	Doctrine for Amphibious Operations	U	Orig. 7 62
NWIP 22-1B	The Amphibious Task Force Plan	U	Orig. 6 65
NWIP 22-4A	UDT in Amphibious Operations	C	Orig. 11 65
NWIP 23-1B	Submarine Primary Missions	C	Orig. 7 65
NWIP 23-2B	Submarine Support Operations	C	1 12 66
NWIP 23-9A	Submarine Evasion Manual	C	Orig. 12 62
NWP 24-B	ASW Operations	C	2 11 66
NWIP 24-1A	ASW Classification Manual	C	2 6 66
NWP 26-A	Mining Operations	C	1/2 1 66
NWIP 26-1	Minefield Planning	C	3 11 61
NWP 27-A	Mine Countermeasures Operations	C	Orig. 1 63
NWIP 27-1A	Support to Mine Countermeasures Operations	S	1/1 5 65
NWIP 27-2	Mine Hunting Procedures	C	Orig. 7 64
NWP 28-A	Nuclear Warfare Operations	S	Orig. 10 66
NWIP 29-1	Seal Teams in Naval Special Warfare	S	Orig. 12 62
NWP 37-A	National SAR Manual	U	3 10 63
USN ADD 37-A	Submarine Disaster SAR Operations	U	3 9 66
SUPP 37-A	Wartime SAR Procedures	C	Orig. 8 65
NWP 38-B	Replenishment at Sea	U	1/1 12 65
NWP 39-A	Base Defense	U	1 4 66
NWP 40-A	Harbor Defense	C	Orig. 1 61

publications, that, in our judgment, influence undersea operational requirements were used. Next, the planning objectives were reviewed, together with the General Operational Requirements (GORs), Specific Operational Requirements (SORs), Tentative Specific Operational Requirements (TSORs), Advanced Development Objectives (ADOs), and Technical Development Plans (TDPs). A list of the GORs is given in Table II-2.

The GORs broadly define users' needs and directly reflect naval missions and operations. Following down the documentation chain of requirements for a development effort are the TSOR, a preliminary stated requirement; the SOR, a stated need; and the ADO, which indicates the direction of experimental development prior to an assumed military usefulness and which sometimes precedes the SOR.

The SORs, TSORs, and ADOs are organized under the particular GORs listed here. They are indicated on the matrix prepared during this study (Table II-2), when they directly or indirectly indicate a particular underwater functional requirement corresponding to the established list. The number or numbers assigned in each square correspond to a particular referenced document in the Reference Requirement List,* which states requirements and provides the details supporting those requirements. These documents, together with the NWPs and the NWIPs, form the basis of current operational requirements officially stated by CNO.

Concurrent with the review of the above naval documents, discussions were held with some potential users in the Navy Department concerning MAN-IN-THE-SEA capabilities and developments; these discussions uncovered other current and possible future potential undersea operations that were not described in the listed documents. The previously cited documents,

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* The Reference Requirements List is presented in the classified addendum to this report.

Table II-2

GENERAL OPERATIONAL REQUIREMENTS

10 Strike Warfare	20 Antisubmarine Warfare	30 Command Support	40 Operational Support
11 Airborne Attack	21 Airborne ASW	31 Command Control	41 Logistics
12 Surface Attack	22 Surface ASW	32 Naval Communications	42 Vacant
13 Submarine Attack	23 Submarine Surveillance	33 Electronic Warfare	43 Personnel
14 Amphibious Assault	24 Undersea Surveillance	34 Navigation	44 Astronautic Support
15 Strategic Deterrence	25 Mining	35 Ocean Surveillance	45 Aviation Support
16 Airborne Antiair	26 Mine Countermeasures	36 Reconnaissance and Intelligence	46 Ship Support
17 Surface Antiair	27 ASW Ancillary Support	37 Environmental Systems	47 Ordnance Support
18 Vacant		38 Special Warfare	48 NBC Defense

together with the discussions, provided most all of the Navy's stated or contemplated requirements for underwater operations currently envisioned for the near future.

If, however, the time scale for future operations is projected into the mid-1970s and early 1980s, the current stated naval undersea operational requirements are not complete, and it became necessary to determine plausible naval undersea operations and the attendant technological requirements from other sources.

Future undersea naval requirements that are likely to evolve are those related to future operations as indicated in the Naval Strategic Studies, Mid-Range and Long Range Guidance, Mid-Range Objectives, and Naval Support Plan. The requirements stated in these studies are much broader than, for example, the specific requirements as stated in a SOR. These long range studies (see Fig. II-1) helped to provide overall documentation for the development of naval underwater operational requirements of the future.

In conjunction with the foregoing sources, the project team sought information on possible future mission concepts from U.S. Naval Laboratory personnel in the R&D phases of weapons systems that are generated elsewhere within the Navy or DOD or by their respective contractors. Past studies that provided some of the projected missions and operations requirements included the following:

1. Study by the Office of the Chief of Naval Operations (OP-03) that identified the U.S. Navy Deep Submergence and Ocean Engineering program for 1970-80 (Ref. 1).*
2. Study by the U.S. Naval Ship Research and Development Laboratory, Panama City, Florida (formerly the Mine Defense Laboratory), that analyzed the capabilities required by military divers in 1980 (Ref. 2).

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* References are given in Section VII.

3. Study by the Nortronics Division of Northrop, Palos Verdes, California, that identified saturated diver requirements for the 1970-80 time frame. The study was supported by the Office of the Chief of Naval Operations and the Deep Submergence Systems Project Office (Ref. 3).

4. Study by Bio-Dynamics, Inc., Cambridge, Massachusetts, for the U.S. Navy Special Projects Office that suggested oceanographic utilization of MAN-IN-THE-SEA concepts (Ref. 4).

5. The panel reports of the Commission of Marine Science, Engineering, and Resources that recommended an overall plan for a national oceanographic program to meet present and future national needs (Refs. 5, 6, 7).

During the progress of the study the project team visited various naval agencies and laboratories to gain first hand knowledge of the projections made by personnel that are closely involved in naval underseas activities. The agencies and laboratories included, in addition to the Office of Naval Research:

- Deep Submergence Systems Project Office
- Supervisor of Salvage, Ship Systems Command
- Office of the Chief of Naval Materials (NAVMAT)
- Naval Facilities and Engineering Command
- Naval Civil Engineering Laboratory, Port Hueneme
- Naval Undersea Research and Development Center, San Diego.

Table II-3 is a matrix representing results of the completed mission and operational requirements review. The naval mission requirements in the various documents were interpreted and organized under ten broad, general underwater mission requirements stated in terms of functional operations. They are: surveillance, reconnaissance, mining, navigation, recovery, facilities installation, salvage, repairs, support, and habitat development.

Table II-3

MISSION AND FUNCTIONAL OPERATIONAL MATRIX

Planning Documents					Planning Objectives: Strike Warfare								Antisubmarine Warfare							Command Support								Operational Support								
NSS Naval Strategic Studies	NMRG Naval Mid-Range Guidance	NMLG Naval Long Range Guidance	MRO Naval Mid-Range Objectives	NSP Naval Support Plan	11 Airborne Attack	12 Surface Attack	13 Submarine Attack	14 Amphibious Assault	15 Strategic Deterrence	16 Airborne Antiair	17 Surface Antiair	18 Vacant	21 Airborne ASW	22 Surface ASW	23 Submarine Surveillance	24 Undersea Surveillance	25 Mining	26 Mine Countermeasures	27 ASW Ancillary Support	31 Command-Control	32 Naval Communications	33 Electronic Warfare	34 Navigation	35 Ocean Surveillance	36 Reconnaissance and Intelligence	37 Environmental Systems	38 Special Warfare	41 Logistics	42 Vacant	43 Personnel	44 Astronautic Support	45 Aviation Support	46 Ship Support	47 Ordnance Support	48 NBC Defense	Undersea Functional Operations
																			13								15			1			*			Surveillance
																																				• Landing beach area
																																				• Enemy harbor
																																				• U.S. harbor protection
																																				• Inshore USW
																								2												• USW all ranges and depths
																			13								15			1			*			Reconnaissance
																																				• Beach area
																																				• Enemy harbor
																																				• Mining environment
																			13											1			3,4 8,9			Mining
																																				• Mine hunting and countermeasures
																																				• Mine plants
																																				• Disarm mine
																																				Interrogate mine fields
																							14					2					3,4			Navigation Surveys
																												2		1			†			Recovery
																																	16			• Small objects
																																				•• Torpedoes
																																				•• Nuclear weapons
																																				•• Space hardware
																																	6			• Large objects
																												2		1			3,4 18			Facility Installations
																																				• Sonar array
									11																										17	• Bottom mounted ULM
																																				• Navigation markers
																																				• Cable laying and inspection
																																				• General construction
																												2		1			3,4 5			Salvage
																																				• Ships
																																				• Aircraft
																												1					3			Repairs
																																				• In port
																																				• Underway
																												2					3,4 5,18			Support
																																				• Oceanographic
																																				• Sub rescue personnel
			20																																	• Undersea logistics
																												2		1			3,4 18			Habitat Development

* = Nos. 3, 4, 8, 9, and 13

† = Nos. 3, 4, 10, 13, and 18

Note: Numbers in boxes, above, refer to the Reference Requirements first given in the classified addendum to this report.

Table II-3 (Concluded)

MISSION AND FUNCTIONAL OPERATIONAL MATRIX

Operational Doctrine: NWP 11-A Naval Operational Planning	NWP 22-A Doctrine for Amphibious Operations	NWIP 22-1B The Amphibious Task Force Plan	NWIP 22-4A UDT in Amphibious Operations	NWIP 23-1B Submarine Primary Missions	NWIP 23-2B Submarine Support Operations	NWIP 23-9A Submarine Evasion Manual	NWP 24-B ASW Operations	NWIP 24-1A ASW Classification Manual	NWP 26-A Mining Operations	NWIP 26-1 Minefield Planning	NWIP 27-A Mine Countermeasures Operations	NWIP 27-1A Support to Mine Countermeasures Operations	NWIP 27-2 Mine Hunting Procedures	NWP 28-A Nuclear Warfare Operations	NWIP 29-1 Seal Teams in Naval Special Warfare	NWP 37-A National SAR Manual	USN ADD 37-A Submarine Disaster SAR Operations	SUPP 37-A Wartime SAR Procedures	NWP 38-B Replenishment at Sea	NWP 39-A Base Defense	NWP 40-A Harbor Defense	Undersea Functional Operations
																						Surveillance
	✓		✓		✓				✓	✓	✓	✓			✓							● Landing beach area
	✓		✓		✓				✓	✓					✓							● Enemy harbor
									✓	✓	✓	✓									✓	● U.S. harbor protection
	✓		✓				✓		✓	✓					✓						✓	● Inshore USW
							✓															● USW all ranges and [illegible]
															✓							Reconnaissance
	✓		✓		✓				✓	✓	✓	✓			✓							● Beach area
	✓		✓		✓				✓	✓	✓	✓			✓							● Enemy harbor
	✓		✓		✓				✓	✓	✓	✓										● Mining Environment
									✓													Mining
	✓		✓								✓	✓	✓								✓	● Mine hunting and countermeasures
	✓				✓				✓	✓											✓	● Mine plants
			✓							✓	✓										✓	● Disarm mine
										✓	✓	✓									✓	● Interrogate mine fields
																						Navigation Surveys
																						Recovery
																						● Small objects
																						● Torpedoes
			✓																			● Nuclear weapons
																						● Space hardware
																						● Large objects
																						Facility Installations
							✓															● Sonar array
																						● Bottom mounted UIM
																						● Navigation markers
							✓															● Cable laying and inspection
																						● General construction
																						Salvage
																						● Ships
																						● Aircraft†
																						Repairs
																						● In port
																						● Underway
																						Support
	✓	✓	✓		✓		✓		✓	✓	✓	✓	✓		✓				✓		✓	● [illegible]
																	✓					● [illegible]
	✓	✓	✓				✓												✓			● [illegible]
																						[illegible]

* - Nos. [illegible], 4, 8, 9, and 13
† - Nos. [illegible], [illegible], 4, 10, 13, and 14

Note: Numbers in boxes, above, refer to the Reference Requirements first given in the classified addendum to this report.

The list of planning documents and related underwater functional operations in the matrix provides an immediate cross reference, showing which planning documents generate and provide specific requirements and the particular underwater functional operation these planning documents are concerned with.

The NWPs and NWIPs are broad naval warfare planning documents, therefore, checks only have been used for cross referencing.

III GENERALIZED TASK SPECTRUM

The utility of a specific undersea system, or combination of systems, in accomplishing the undersea missions and operations identified in the previous section is dependent primarily upon the tasks associated with each mission and operation. A critical step in the determination of the application of MAN-IN-THE-SEA concepts is, therefore, the identification of the undersea tasks and their association with the appropriate missions and operations.

Mission and operation related tasks were derived through the following method. Three operations listed in Table II-3 were selected for task analysis. These were: (1) recovery, represented by a simple small object pickup operation; (2) salvage, represented by an aircraft salvage and a small ship salvage operation; and (3) undersea construction, represented by a permanent anchor emplacement operation and an underwater facilities construction operation. Recovery and salvage operations were selected because they are a real current Navy requirement and will remain so in the near future. Furthermore, tasks involved in recovery and salvage operations are faily well defined. Undersea construction is a stated Navy requirement for the near future. Tasks involved in construction are currently being defined by various ongoing programs.

The range of operations, from solid current requirements of recovery and salvage and on to the near future undersea construction requirements, provided a base for uncovering a spectrum of undersea tasks. The results of the task analysis effort are presented in Appendix A.

In addition to those tasks identified for the three selected operations, a compendium of undersea tasks was put together through a review of various sources (Refs. 1-7). The studies reviewed were conducted to identify current and projected design requirements for divers' tools and to apply the findings to the study of deep submergence vehicles and vehicle design requirements. The compendium of tasks resulted from a fairly exhaustive search and definition of current and foreseeable undersea tasks. While many studies provide breakdowns of undersea tasks, it became apparent very early in the review that the referenced studies represented the consensus on possible underwater tasks. For instance, oceanographic studies indicate that instrument pickup, transportation, and placement are the required set of underwater tasks. The vehicle manipulator studies specify torpedo pickup and transportation as a set of underwater tasks. It is obvious that both sets of tasks correspond to the same general set of undersea activities. By correlating the tasks described in each study, including those described in the task analysis effort of this study (Appendix A), a list of generalized tasks was generated. The generalized task spectrum covers nearly all the current undersea tasks and foreseeable future undersea tasks. For convenience, the generalized task spectrum is divided into four classes of activities. Class I is the general search or location task; Class II includes the observation, surveying, and measurement tasks; Class III includes the simple pickup, transport, and placement tasks; and, finally, Class IV represents the whole group of manipulative activities that include the attachment, detachment, application, and excavation tasks. These tasks are briefly described below.

- <u>Class I: Search</u>

  The search task includes activities associated with the location of lost objects, wrecks, submarines, mines, bottom features, and so forth. The search/location task is conducted over a large area of the ocean bottom from a moving platform with visual, acoustic, electromagnetic, magnetic, or electric sensors.

- <u>Class II</u>:

  - <u>Observation</u>

    The observation task entails the monitoring of activities from a fixed platform through the use of visual, acoustic, electromagnetic, magnetic, or electric sensors. Examples of this task are harbor surveillance, submarine detection, and swimmer detection.

  - <u>Survey</u>

    The survey task includes such activities as the inspection of wrecks, recording via photography or sonar, and determination of general conditions of underseas structures.

  - <u>Measure</u>

    The measurement task includes such activities as the determination of bottom slope, bottom hardness, water temperature, and water turbidity. The majority of oceanographic data gathering activities might be classified as measurement tasks.

- <u>Class III</u>:

  - <u>Pickup</u>

    The pickup task entails activities associated with the recovery of small objects. Recovery of torpedoes, space re-entry bodies, bombs, and the like, requiring only simple grappling action are simple pickup tasks.

  - <u>Transport</u>

    The transport task is simply the moving of an object from point A to point B.

  - <u>Place</u>

    The placement task entails activities associated with the deployment of bottom moored mines, bottom navigation markers, or oceanographic instruments.

- Class IV:

  - Attachment

    The attachment task includes a whole range of activities--from the mounting of a patch on wrecks, to the mounting of lifting padeyes to recover objects, to the hooking up of connectors, such as air hose or pipelines. The task can be broken down into the subtasks of drilling, bolting, riveting, hooking up, clamping, and so forth.

  - Detachment

    The detachment task includes a spectrum of activities ranging from removal of sections of a salvage object, through the clearing of lines, to the removal of marine growth from undersea objects. The task can be broken down into the subtasks of drilling, burning, hammering, chipping, scraping, and the like.

  - Apply

    The application task includes such activities as the placement of foam for the flotation of wrecks and the application of paint on undersea structures.

  - Excavate

    The excavation task includes such activities as trenching, tunneling, coring, and dredging.

Each Navy undersea mission and operation defined in Table II-3 has an associated set of tasks. These mission/operations and task relationships are given in Table III-1. The X's identify tasks associated with each subdivision of a major operation, e.g., small object or large object recovery, within the overall functional operation heading of recovery. All tasks associated with an overall functional heading, such as "Recovery," "Facilities Installation," or "Salvage" are shown in the shaded rows.

Table III-1

NAVAL UNDERSEA MISSIONS, OPERATIONS, AND ASSOCIATED TASKS

Undersea Missions and Operations \ Generalized Task Spectrum	Class I	Class II			Class III			Class IV			
	Search/Locate	Observe	Survey	Measure	Pickup	Transport	Place	Attach {Drill, Bolt, Rivet, Connect/hookup, Clamp}	Detach {Drill, Burn, Saw, Hammer, Chip, Scrape, Wipe}	Apply (Fill) {Hose, Paint}	Excavate {Core, Dredge, Trench, Tunnel}
Surveillance		■	■		■	■	■				
Landing beach area		X	X		X	X	X				
Enemy harbor		X	X		X	X	X				
U.S. `arbor protection		X	X		X	X	X				
Inshore USW		X	X		X	X	X				
USW all ranges & depths		X	X		X	X	X				
Reconnaissance	■		■	■	■	■	■				
Beach area	X		X	X	X	X	X				
Enemy harbor	X		X	X	X	X	X				
Mining environment	X		X	X	X	X	X				
Mining	■	■	■	■	■	■	■	■	■		■
Mine hunting and countermeasures	X		X	X		X	X				
Mine plants						X	X				
Disarm mine								X	X		X
Interrogate mine fields	X	X	X								
Navigation Surveys	■		■	■	■	■	■				
Recovery	■		■	■	■	■	■	■	■	■	■
Small object	X		X		X	X					
• Torpedoes	X		X		X	X					
• Nuclear weapons	X		X		X	X					
• Space hardware	X		X		X	X					
Large object	X		X	X	X	X	X	X	X	X	X
Facility Installations			■	■	■	■	■	■	■	■	■
Sonar array (align & repair)			X	X	X	X	X	X	X	X	
Bottom mounted ULM			X	X	X	X	X	X	X	X	X
Navigation markers			X	X	X	X	X				
Cable lay.ng & inspection			X	X	X	X	X	X			
General construction			X	X	X	X	X	X	X	X	X
Salvage	■	■	■	■	■	■	■	■	■	■	■
Ships	X	X	X	X	X	X	X	X	X	X	X
Aircraft	X	X	X	X	X	X	X	X	X	X	X
Repairs											
In port (wet dock)								X	X	X	
Underway								X	X	X	
Support	■	■	■	■	■	■	■	■	■	■	■
Oceanographic data		X	X	X	X	X	X	X	X	X	X
Sub rescue personnel	X	X	X			X	X	X	X	X	X
Underwater logistics		X			X	X	X	X	X		
Habitat Development		■	■	■	■	■	■	■	■	■	■

■ Undersea mission areas   [X] Undersea operations within the broad mission areas

IV UNDERSEA WORK SYSTEMS

A. General

The growing interest and concern with the exploration of the oceans and the exploitation of ocean resources have resulted in the evolution of a spectrum of systems for accomplishing undersea tasks. These undersea work systems are separated into two distinct classes in terms of how man can be utilized in the system. The first system category employs techniques that place man in the ambient pressure environment and enable him to achieve direct contact with his working environment. These ambient pressure systems, referred to as "MAN-IN-THE-SEA" or "Wet" systems, are the focal point of this application study. The second system category employs techniques that enable man to conduct undersea operations in a normal atmospheric pressure environment. The atmospheric environment is provided through the use of a protective pressure vessel or through the location of a man on the ocean surface who operates a remote controlled device. The atmospheric systems, referred to as the "Shirtsleeve" or "Dry" systems, are alternative techniques in accomplishing underwater work whereby man is not exposed to the hazards of the ambient pressure environment.

The various options within each major undersea work system category are delineated in this section, together with a summary description of their characteristics. More detailed descriptions of the MAN-IN-THE-SEA systems and the alternatives to MAN-IN-THE-SEA systems are provided in Appendix B.

B. MAN-IN-THE-SEA Systems Options

A wide variety of configurational options is possible in integrating MAN-IN-THE-SEA components into an undersea work system. The selection of a particular configurational option is governed by the specific work site environment and task requirements. Seven generalized systems were configured to provide baseline systems for this study. These systems are categorized in terms of the support components employed in the system, i.e., surface ship support or submarine support. The seven options of MAN-IN-THE-SEA systems are listed in Table IV-1, together with the identification of the principal components that make up each option. Each of the options is illustrated and described in Figs. IV-1 through IV-7.

Table IV-1

MAN-IN-THE-SEA SYSTEMS OPTIONS

MAN-IN-THE-SEA Systems Options	Principal MAN-IN-THE-SEA Systems Components								Notes
	Surface Support Ship	Subsurface Support Ship (Submarine)	Subsurface Support Habitat	Decompression Chamber	Personnel Transport Capsule (PTC)	Personnel Transport Vehicle (PTV)	Free Swimming--Personnel Support	Tethered--Personnel Support	
I Direct Surface Supported System (Fig. IV-1)				1			2	2	1. Emergency use only 2. Either free swimming or tethered
II Augmented Surface Supported System--PTC (Fig. IV-2)				3					3. On the surface support ship
III Augmented Surface Supported System--PTV (Fig. IV-3)									
IV Augmented Surface Supported System--Habitat (Fig. IV-4)					4	4			4. Either PTC or PTV
V Direct Subsurface Supported System (Fig. IV-5)				5					5. On the submarine
VI Augmented Subsurface Supported System--PTV (Fig. IV-6)									
VII Augmented Subsurface Supported System--Habitat (Fig. IV-7)						6			6. Optional personnel transport

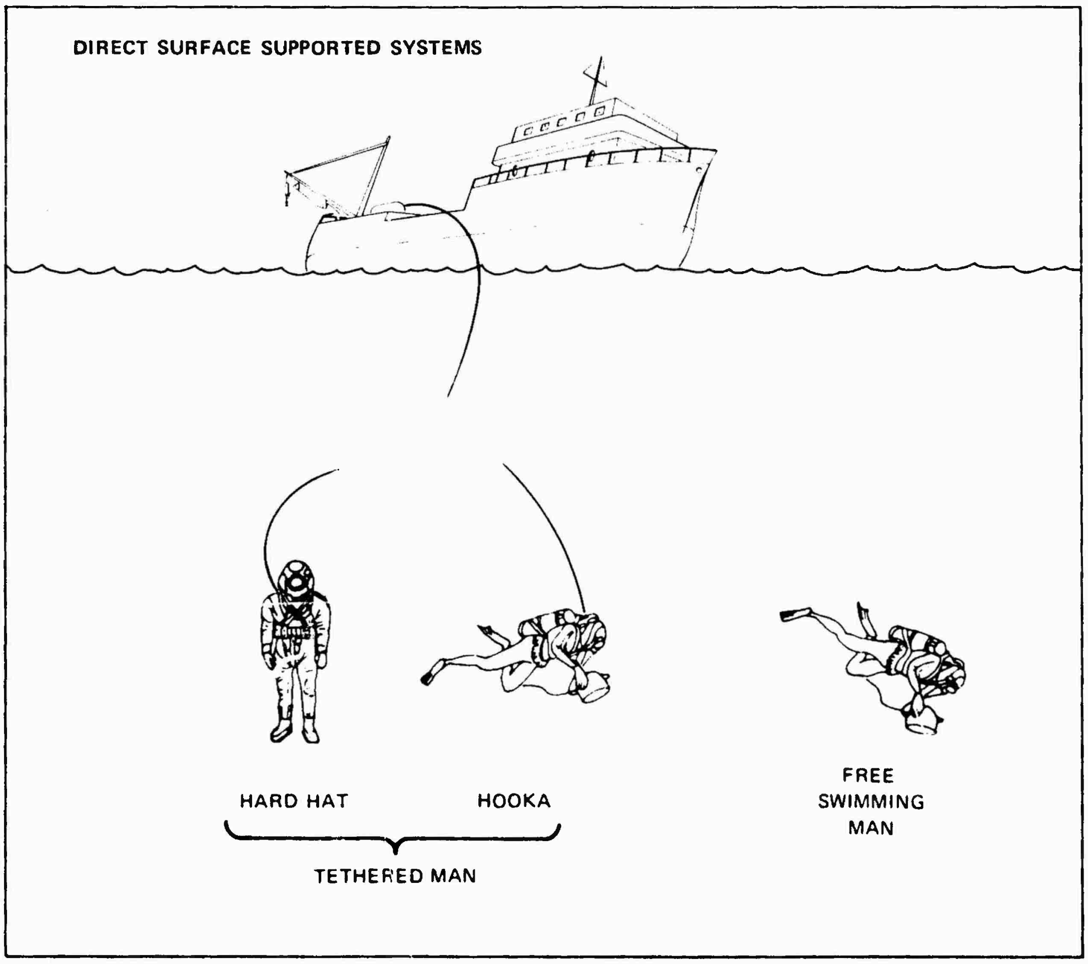


FIGURE IV-1 MAN-IN-THE-SEA SYSTEM OPTION I

The most familiar form of a MAN-IN-THE-SEA system is the tethered or free swimming man operating directly from a surface support platform. The three specific forms of DIRECT SURFACE SUPPORTED SYSTEMS are described in the following:

The **Hard Hat** diver, tethered to a breathing gas supply on the surface ship, is the earliest form of the MAN-IN-THE-SEA system. The average diving depth for compressed air dive is 150-200 ft, the limit being established by individual susceptibility to nitrogen narcosis. Working dives to 300-350 ft can be accomplished with the use of a helium-oxygen mixed gas supply. The time limit is established primarily by the physical endurance of the diver. The primary functional limit of the tethered hard hat diver is his mobility and maneuverability.

The **Free Swimming** diver overcomes the mobility and maneuverability constraints of the hard hat diver. However, a compromise is made on diving duration. Time constraints are established by the limited life support stores that a diver can carry and his dependency upon the particular breathing system used. Standard open cycle air SCUBAs have a limited depth-time function. Closed cycle oxygen rebreathers are limited by oxygen toxicity to use above 33 ft, however, they possess time and covertness advantages over the open air SCUBA. Semiclosed mixed gas SCUBAs enable greater depth-time capability than either of the two systems mentioned above. An advanced closed cycle mixed gas system capable of 4-6 hr at 600 ft has just been introduced that overcomes many of the present day free swimmer limitations.

The **Tethered Swimmer** (Hooka) is a compromise solution to the mobility constraints of the hard hat diver and the time constraints of the free swimmer. The tethered swimmer is supplied by surface breathing gas stores of compressed air or mixed gases.

All three forms of the direct surface supported systems described above use the technique of ascent decompression. That is, the diver is required to remain in the water at predetermined depth stages and durations during ascent. Decompression facilities are on hand for emergency purposes.

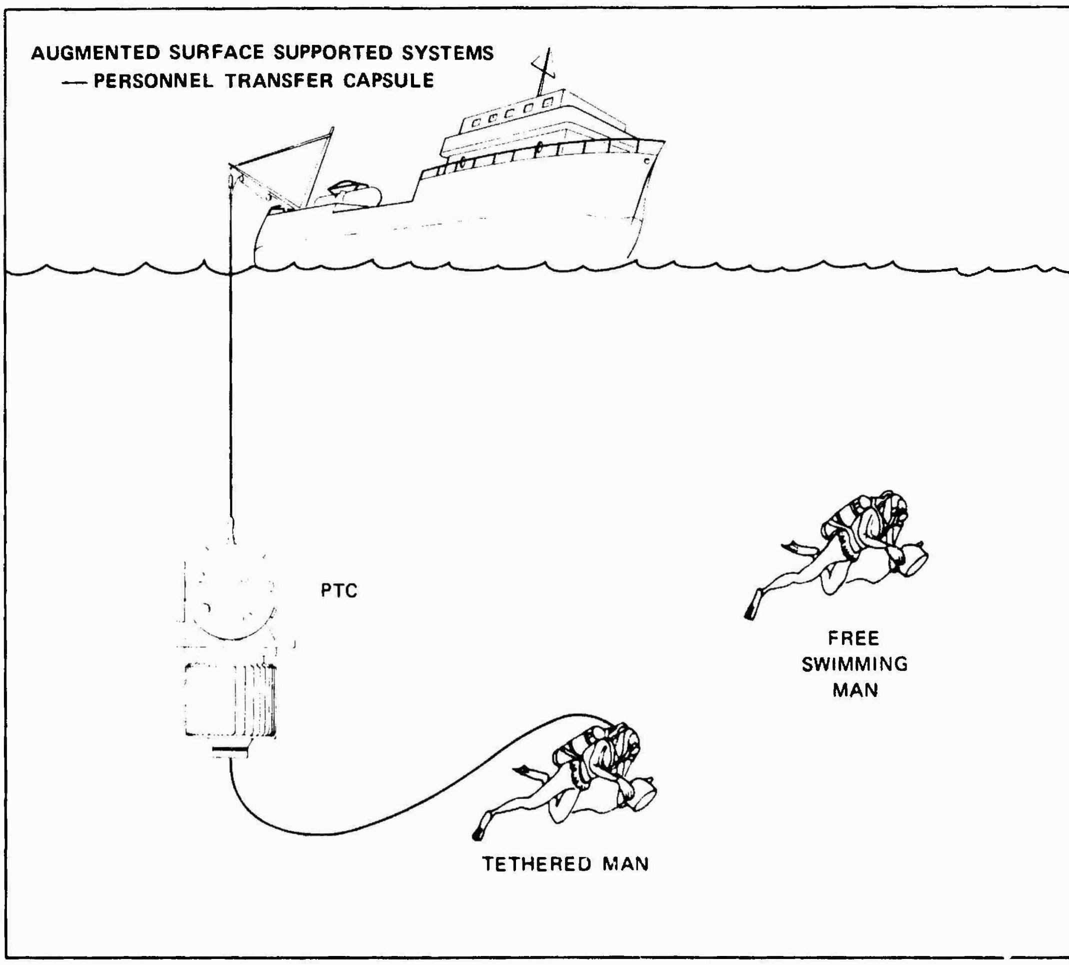


FIGURE IV-2 MAN-IN-THE-SEA SYSTEM OPTION II

The first category of AUGMENTED SURFACE SUPPORTED SYSTEMS is one that uses the personnel transfer capsule (PTC) together with a deck decompression chamber (DDC)*. The PTC serves a diving team as the transfer elevator to and from their underwater work site while maintaining a required pressurized breathing environment of compressed air or mixed gas. The PTC can be used in two ways. In its principal use, the capsule carries divers to the work site or to the spot from which diver excursions will be made. The capsule maintains the diver in an air or mixed gas atmosphere that has a gas pressure equal to the sea water pressure at the diver's destination depth. At the destination depth a diver may leave the capsule through a lower lock. The diver may operate out of the PTC on a tether that supplies breathing gas for long work periods, or he may use self-contained equipment as an untethered swimmer.

The PTC can also be used as a diving bell, with atmospheric air at surface pressure environment (14.7 psi). The PTC is used for observation and inspection of work or work site. If inspection establishes that divers are needed, the PTC can then be pressurized to ambient pressure and divers deployed for in-water work. There are major economic advantages to this way of using the PTC.

The DDC provides a pressurized environment aboard the surface support ship compatible with the ambient pressure condition of the work site. An entrance lock provides a pressure connection between the DDC and the PTC, allowing transfer of divers while maintaining their pressurized environmental conditions. In addition to its decompression function, the DDC also provides the function of a habitat for multiple dive operations. That is, the diver can make many trips between surface and work site without the need for decompression after each dive. He is maintained at work site ambient pressure in the DDC. Only one decompression cycle is needed after completion of the multiple dive operation. The terms "bounce dive" and "subsaturation dive" have been applied to the technique of decompression after each dive. The term "saturation dive" is used to refer to the technique of a single decompression cycle after a long term multiple dive operation.

*A more detailed description of the use of PTC and DDC is presented in Appendix B

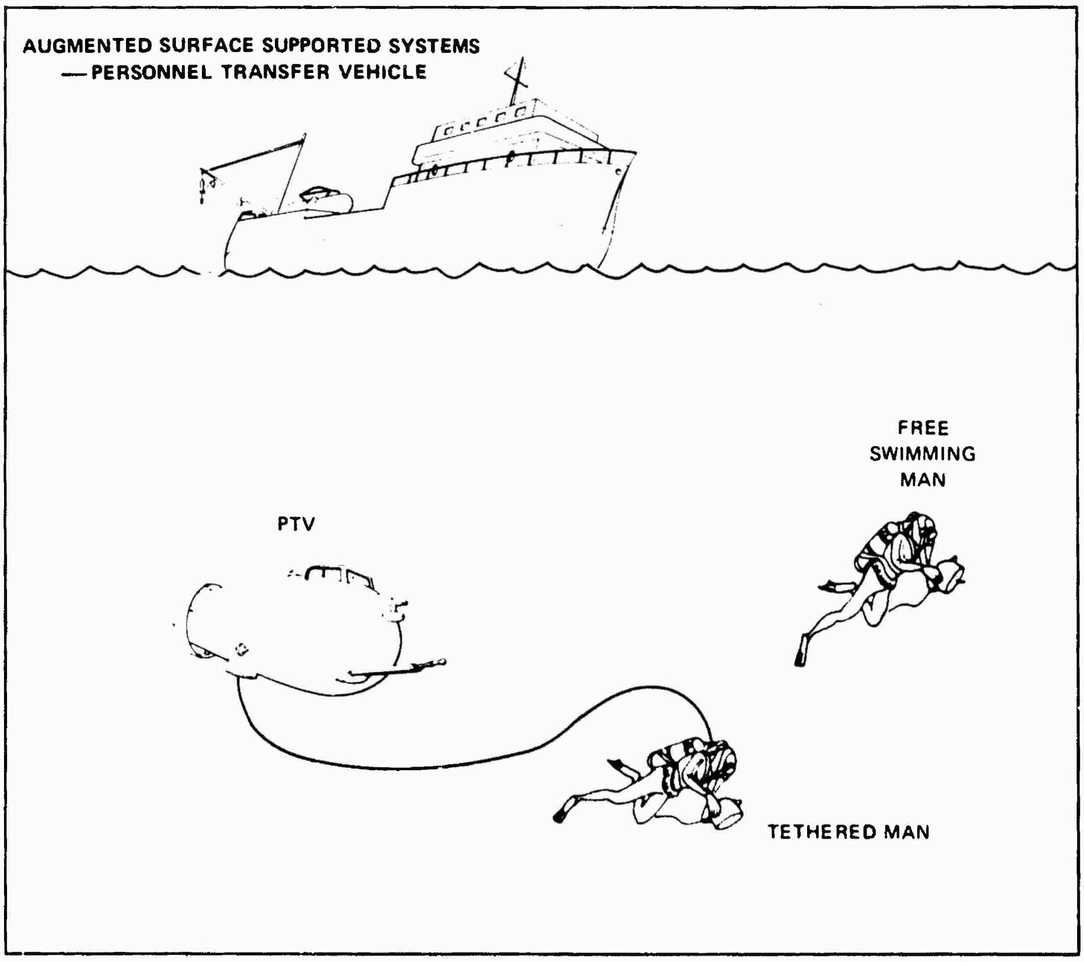


FIGURE IV-3 MAN-IN-THE-SEA SYSTEM OPTION III

The second category of AUGMENTED SURFACE SUPPORTED SYSTEMS uses the personnel transfer vehicle, together with a deck decompression chamber (DDC). The PTV is used in the same manner as the personnel transfer capsule (PTC) described in the preceding system. The PTV has the advantage of horizontal movement over the PTC in its diver transfer and support functions. There are a number of operating vehicles today that have the diver delivery (lock-out) capability, specifically, the Ocean System, Inc., DEEP DIVER; the North American Rockwell, BEAVER MARK IV (ROUGHNECK); and the Lockheed, DEEP QUEST, to name a few. The common feature of all PTVs is the use of an atmospheric pressure compartment and a diver lock-out compartment. The vehicle pilot and/or a technical observer operates from the atmospheric pressure compartment. The divers are transported in the lock-out compartment.*

The flexibility of this system lies in the fact that the decision to use divers can be delayed until a thorough inspection is conducted and a work plan is developed in an atmospheric condition. Then without delay, divers can be deployed to do the work. The scheme eliminates unnecessary exposure of divers to ambient pressure with the accompanying long and costly decompression cycles.

*A more detailed description of the PTV is presented in Appendix B

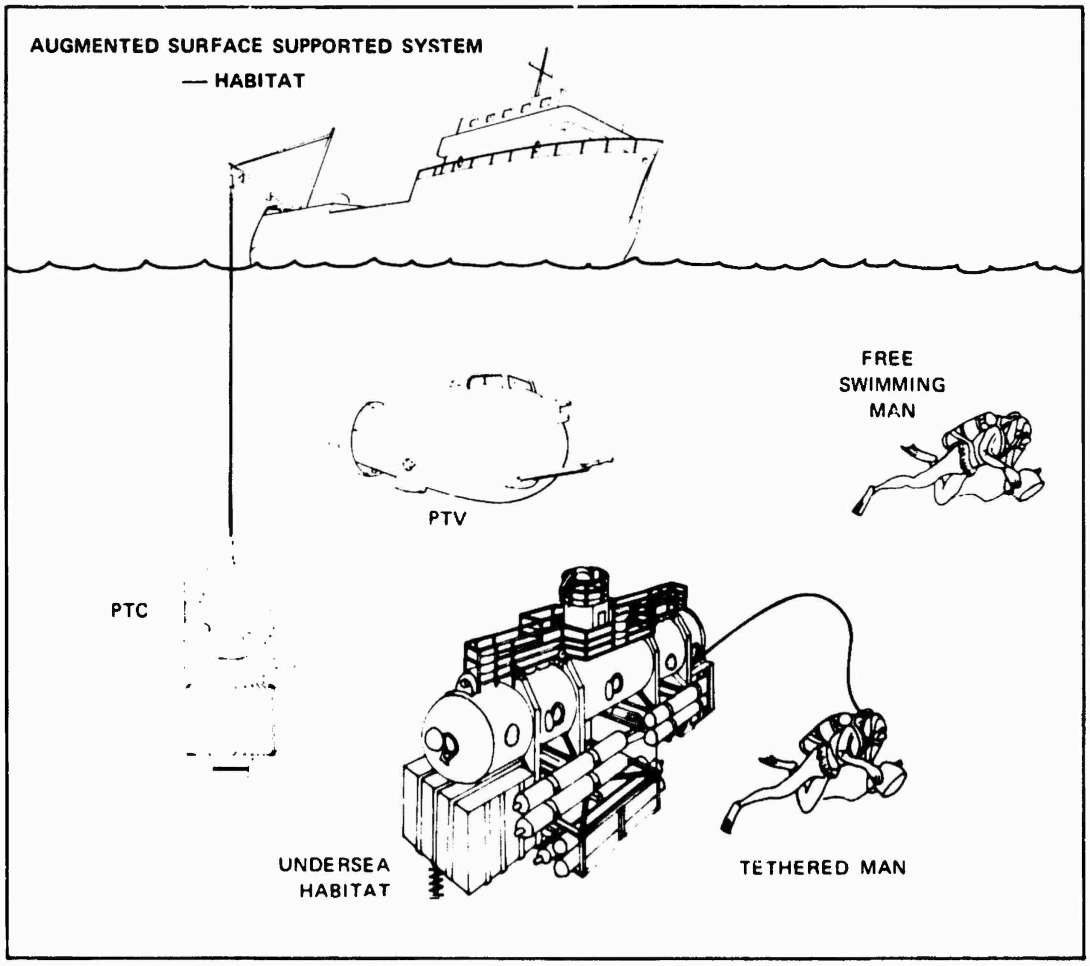


FIGURE IV-4 MAN-IN-THE-SEA SYSTEM OPTION IV

The third category of AUGMENTED SURFACE SUPPORTED SYSTEMS employs an undersea habitat located at the work site. The habitat provides the living quarters from which men can make excursions to the job site. The habitat maintains an ambient pressure environment, utilizing the required gas mixture for the specific operating depth (air or helium-nitrogen-oxygen mixtures). The use of the undersea habitat provides prolonged undersea work capability by: (1) capitalizing on the unique capabilities of saturation diving techniques, i.e., the improved ratio of on job time vs decompression time, and (2) reducing the dependence on surface support, which enables uninterrupted work in rough weather conditions.

In operation the habitat would be transported to the job site and emplaced by the surface support ship. Personnel could ride the habitat to depth or they could be delivered to the habitat by the personnel transfer capsule or the personnel transfer vehicle. After completion of the work cycle personnel are returned to the surface via the PTC or PTV and decompressed in a decompression chamber on the surface support ship. The personnel can also remain in the habitat and be decompressed in the habitat during recovery. The combined use of the habitat as a decompression facility has evolved a system referred to as the MOBILE HABITAT concept.

Examples of augmented surface supported systems are the U.S. Navy SEALAB systems, the TEKTITE system*, and the MOBILE HABITAT system of Makai Range, Inc.

*See Appendix B

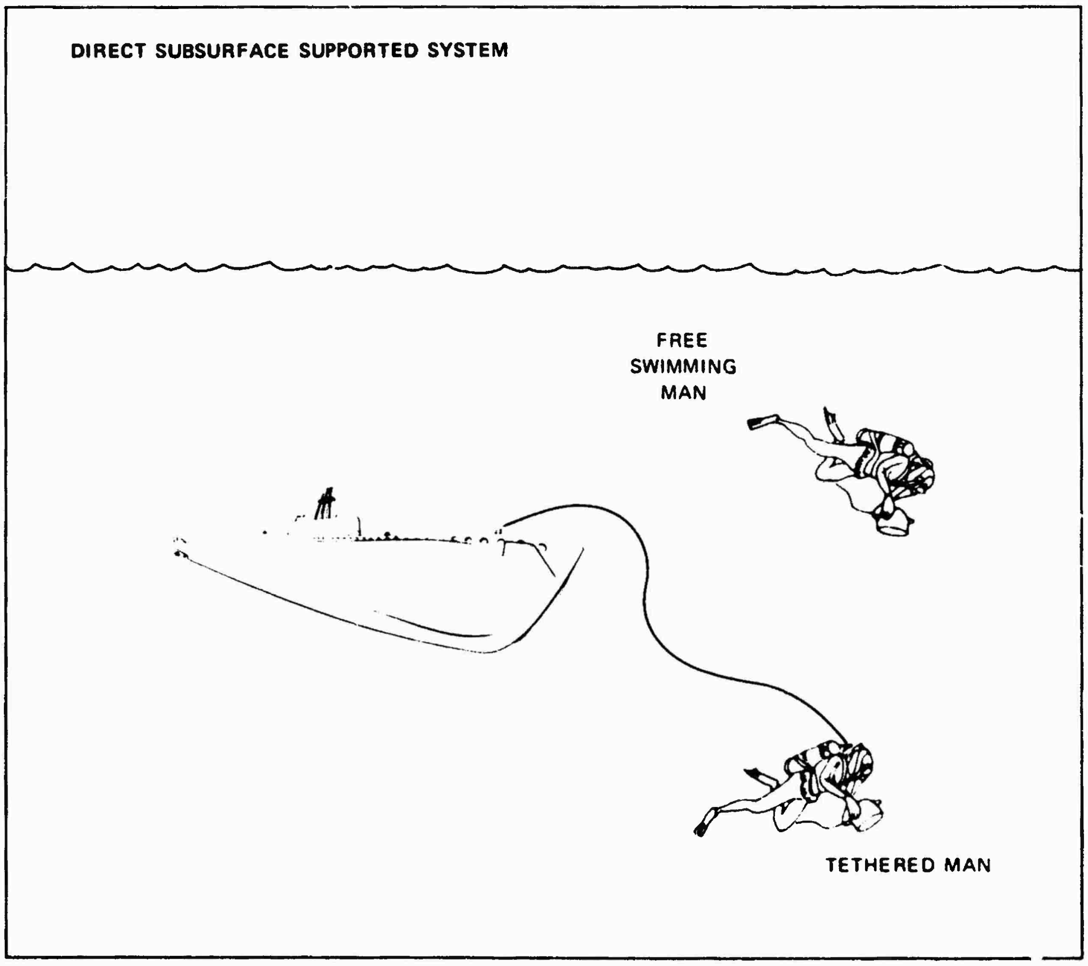


FIGURE IV-5 MAN-IN-THE-SEA SYSTEM OPTION V

The DIRECT SUBSURFACE SUPPORTED SYSTEM is one in which personnel are deployed and supported from a submarine platform. The most familiar form of this system is the deployment of underwater demolition teams (UDT) from submerged submarines. An example of the system is the completed conversion of the guided missile submarine, USS GRAYBACK, into a swimmer transport and support submarine. The submarine is configured for the deployment and recovery of swimmers while submerged through the use of a "lock-out" compartment. The submarine is provided with a decompression chamber. In operation, personnel can be deployed in the free swimming or the tethered mode (see Figure IV-1, MAN-IN-THE-SEA System Option I).

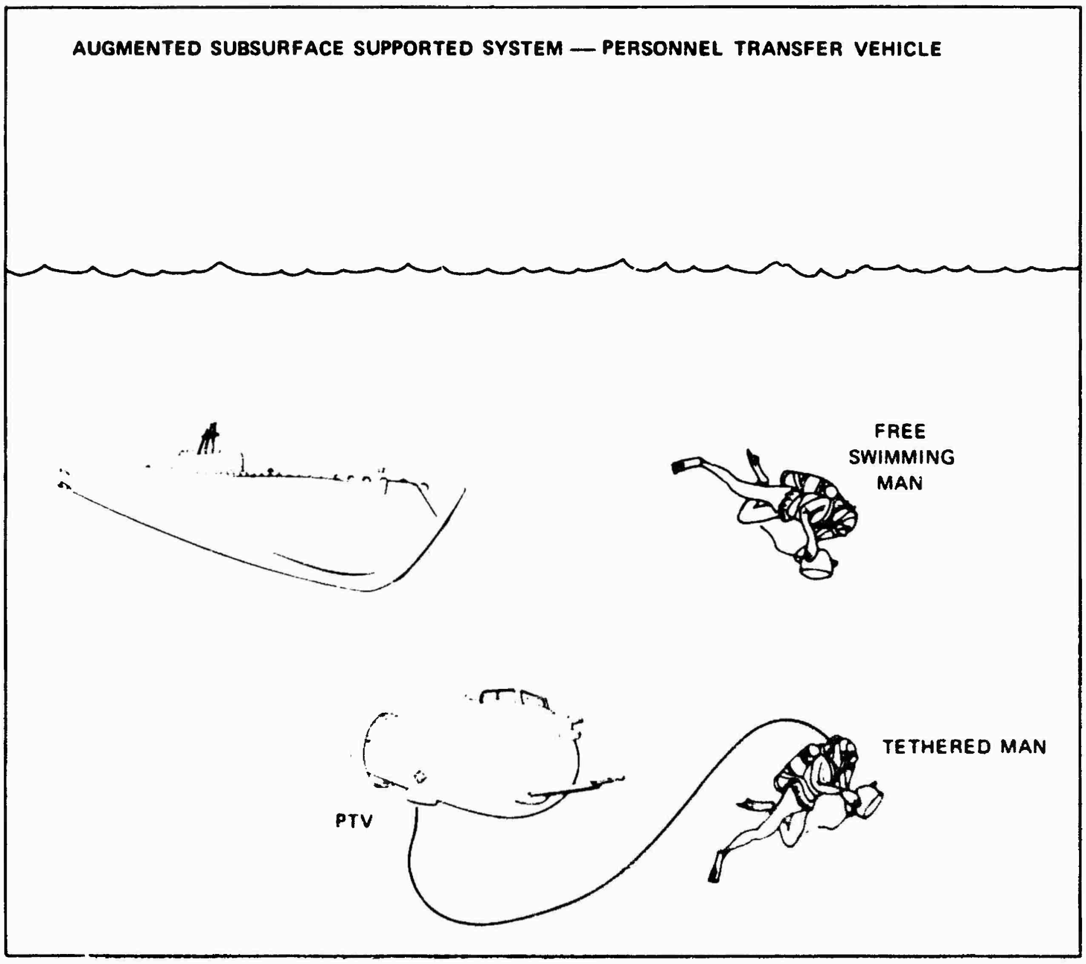


FIGURE IV-6 MAN-IN-THE-SEA SYSTEM OPTION VI

The first category of AUGMENTED SUBSURFACE SUPPORTED SYSTEM uses the personnel transfer vehicle (PTV) as an auxiliary support platform. The primary purpose of the PTV is to provide support of personnel where the larger support submarine may be constrained, e.g., maneuvering space and water depth. The PTV will be transported and deployed from the submarine. Personnel can operate from the PTV in the free swimming or tethered mode as described for the surface supported system (see Figure IV-3, MAN-IN-THE-SEA System Option III). The submarine will contain the required decompression facilities.

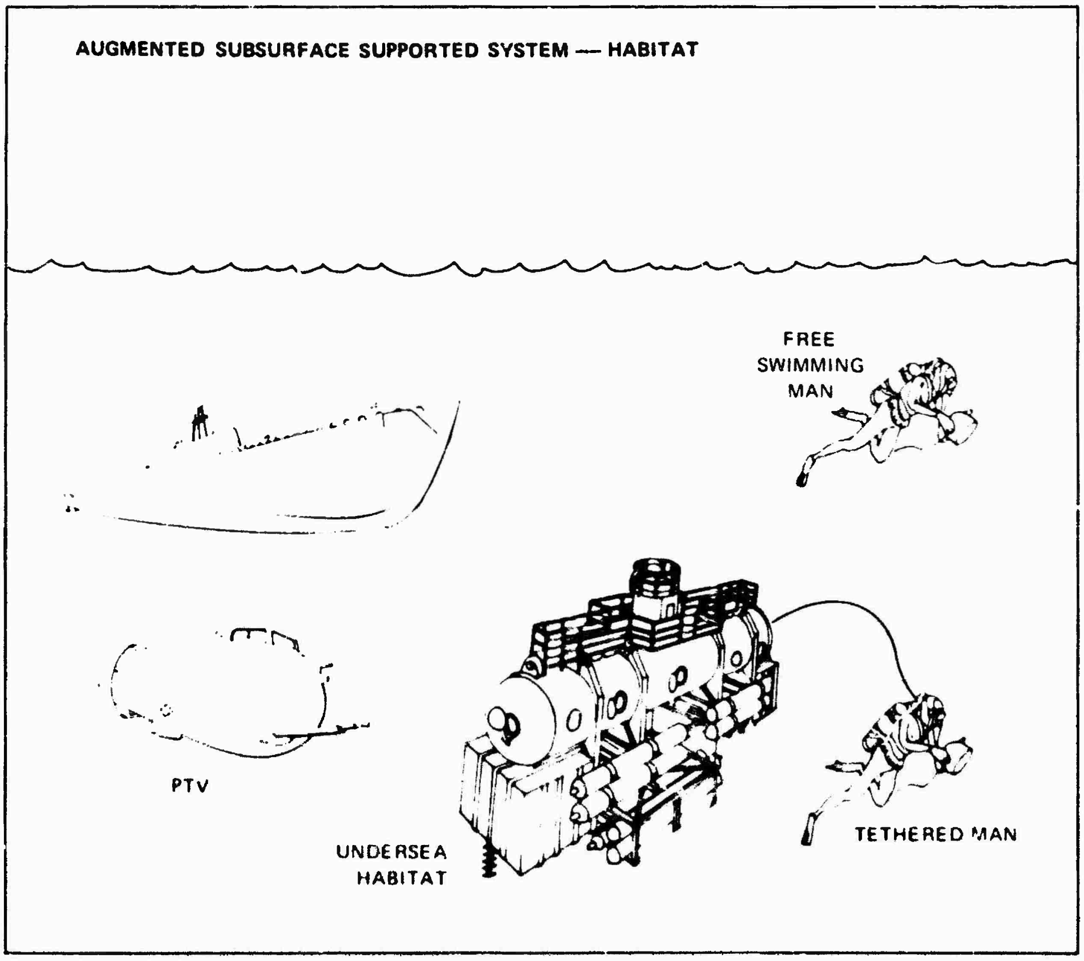


FIGURE IV-7 MAN-IN-THE-SEA SYSTEM OPTION VII

The second category of AUGMENTED SUBSURFACE SUPPORTED SYSTEM uses an undersea habitat. The basic concept is similar to the surface supported system described in Figure IV-4, MAN-IN-THE SEA System Option IV, with the exception that a submarine is used to transport, emplace, and support the undersea habitat. The use of an auxiliary personnel transfer vehicle (PTV) is possible. In operation, the submarine will transport the habitat to the job site and emplace the habitat. The submarine can then leave the habitat and return for resupply, and, finally, the recovery of the habitat and work team. The submarine will be fitted with the required decompression facilities.

C. Alternatives to MAN-IN-THE-SEA Systems

Basic alternatives to MAN-IN-THE-SEA systems include: (1) manned free swimming vehicles, (2) manned tethered vehicles, (3) manned fixed bottom stations, (4) unmanned free swimming vehicles, (5) unmanned tethered vehicles and (6) unmanned fixed bottom stations. The manned free swimming vehicles constitute the largest group of alternatives to MAN-IN-THE-SEA concepts. More than 30 manned submersibles have been developed in the United States by the Navy, other governmental agencies, and commercial operators.

The six basic alternatives can be deployed and supported by surface support platforms or submersible support platforms. Current operational systems are predominantly the surface support types. In addition to surface and mobile submersible support platforms, many of the systems can be deployed from the manned fixed bottom habitat. The current status of the basic alternatives--operational, research and development, or conceptual--as it relates to the three support components, are summarized in Table IV-2.

Examples of each of the basic alternatives are described in Figs. IV-8 to IV-13. These examples represent a small sample of a wide variety of technical approaches within each category of basic alternatives. The examples serve as reference systems for the ensuing comparative analysis studies in Sections V and VI.

Table IV-2

SUPPORT COMPONENT OPTIONS TO BASIC ALTERNATIVES TO MAN-IN-THE-SEA SYSTEMS

Support Component Options	Basic Alternatives to MAN-IN-THE-SEA Systems					
	Manned Systems			Unmanned Systems		
	I	II	III	IV	V	VI
	Free Swimming Vehicles	Tethered Vehicles	Fixed Bottom Station	Free Swimming Vehicle	Tethered Vehicles	Fixed Bottom Station
Surface support platform						
Submersible support platform						
Manned fixed bottom station			Not Applicable			

Operational | Research and Development | Conceptual

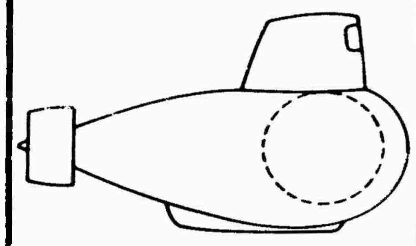
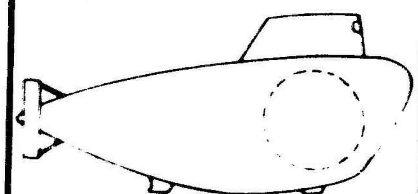
CONFIGURATION	CHARACTERISTICS	DESCRIPTION
ALVIN 	DEPTH 6,000 ft LIFE SUPPORT 8 hr normal, 24 hr maximum SPEED 2 kt cruise, 6 kt maximum RANGE 20-25 nmi DIMENSIONS Length 22 ft, Width 8 ft, Height 12 ft PAYLOAD 1,200 lb CREW 2	The **ALVIN**, which is operated by the Woods Hole Oceanographic Institute under contract to the Office of Naval Research, is performing a wide spectrum of undersea activities. These activities include: inspection of underwater instruments and structures at the Navy's Atlantic Undersea Test and Evaluation Center off Andros Island; oceanographic surveys requiring bottom and water samples, coring, placing and retrieving instruments and markers; photographing; and so forth. The **ALVIN** was used successfully during the search and location of the hydrogen bomb that was lost near Palomares, Spain. This vehicle is equipped with a mechanical manipulator that can handle specialized tools for accomplishing underwater tasks, for example, the bottom coring tools used in the oceanographic survey activities. The manipulator has a grapple hand terminal device that can handle a variety of specially designed tools and instruments. Sensory equipment on the **ALVIN** includes scanning sonar, echosounder, navigational sonar, television cameras, and movie cameras. Communications equipment includes acoustic communications for underwater use and radio communications for surface use.

FIGURE IV-8 BASIC ALTERNATIVE TO MAN-IN-THE-SEA SYSTEM I — MANNED FREE SWIMMING VEHICLE

CONFIGURATION	CHARACTERISTICS	DESCRIPTION
AUTEC 	DEPTH 6,500 ft LIFE SUPPORT SPEED 2 kt cruise, 8 kt maximum RANGE 20-25 nmi DIMENSIONS Length 25 ft, Width 10 ft, Height 15 ft PAYLOAD 1,200 lb CREW 2	The AUTEC vehicle is essentially a second generation version of the ALVIN. Two of these vehicles, AUTEC I and AUTEC II, are being built for the Navy Ship Systems Command. They are intended for use at the Navy's Andros Island operation. The vehicles are to be used for placing electronic systems on the ocean bottom and inspecting, testing, and retrieving them, and for performing oceanographic research. The vehicles also will be capable of conducting or assisting in salvage operations at depths to 6,500 ft. As currently visualized, each vehicle will be equipped with two mechanical manipulators of more advanced design than that of the ALVIN (see Appendix C). Sensory and communications equipment are essentially the same as those on the ALVIN.

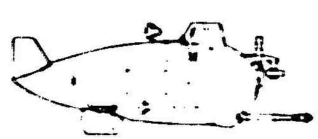
CONFIGURATION	CHARACTERISTICS	DESCRIPTION
BEAVER MARK IV 	DEPTH 2,000 ft LIFE SUPPORT 36 hr SPEED 2.5 kt cruise, 5.0 kt maximum RANGE 20-25 nmi DIMENSIONS Length 24 ft, Width 10 ft, Height 11 ft PAYLOAD 2,000 lb CREW 2 operators, 3 divers	The BEAVER MARK IV submarine work boat was constructed by North American Rockwell Corporation to be used in supporting off-shore oil exploration, drilling, and production operations. The vehicle is equipped with an advanced design manipulator that can handle a variety of tools. The tools, which can be changed underwater, include impact wrenches, stud guns, jet pumps, wire brushes, grinding wheels, and cable cutters. The BEAVER also serves as a mobile platform for MAN-IN-THE-SEA operations, since it contains a diver lock-in/lock-out capability. Sensory and communications equipment are essentially the same as those on the ALVIN and AUTEC vehicles.

FIGURE IV-9 BASIC ALTERNATIVE TO MAN-IN-THE-SEA SYSTEM I — MANNED FREE SWIMMING VEHICLE

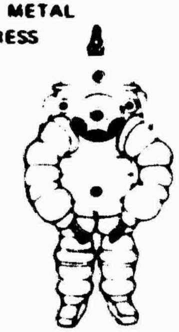
CONFIGURATION	CHARACTERISTICS	DESCRIPTION
ARTICULATED METAL DIVING DRESS 	DEPTH 600 ft LIFE SUPPORT 3 hr SPEED RANGE DIMENSIONS Length Width 4 ft Height 8 ft PAYLOAD CREW 1	ARTICULATED METAL DIVING DRESS consists of: (1) a body formed of three spherical zones superimposed with extensions for the top, arms, and legs, (2) a spherical dome cover, (3) two articulated arms connected to the body through a gimbal spherical articulator, which has revolving joints above the elbow and two pairs of pliers (or other interchangeable tools), (4) two articulated legs for propulsion; (5) a ballast chamber on the back of the body, and (6) two compressed air bottles for serving the ballast chamber and two oxygen bottles for life support. The first metal suit was built in 1935. Since that time more advanced versions have been constructed. The suit is sold commercially by Robert Galeazzi, Ltd, La Spesia, Italy.
CONFIGURATION	**CHARACTERISTICS**	**DESCRIPTION**
GUPPY 	DEPTH 3,000 ft LIFE SUPPORT 8 hr SPEED 5 kt RANGE Unlimited DIMENSIONS Length 20 ft Width 6 ft Height 9 ft PAYLOAD CREW 2	The second example of a manned tethered vehicle is the GUPPY, which is built by Sun Shipbuilding and Dry Dock. This vehicle is a two-man craft tethered to a support ship or oil rig by a 3,000-ft electrical cable. Its unique feature is the availability of 16 kilowatts of high intensity light. Although descriptive data on the vehicle do not specify manipulative capability, there is no reason to assume that manipulators cannot be mounted on it.

FIGURE IV-10 BASIC ALTERNATIVE TO MAN-IN-THE-SEA SYSTEM II — MANNED TETHERED VEHICLE

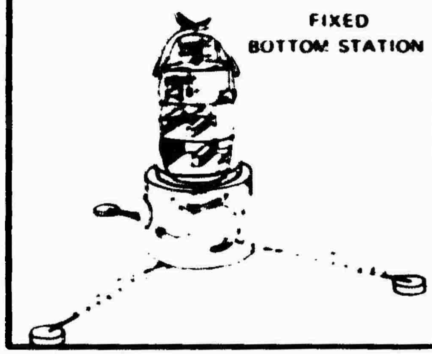
CONFIGURATION	CHARACTERISTICS	DESCRIPTION
FIXED BOTTOM STATION 	DEPTH 6,500 ft LIFE SUPPORT 30 days SPEED RANGE DIMENSIONS Length Width Height PAYLOAD CREW 5	In studies conducted for the U.S. Naval Civil Engineering Laboratory, Port Hueneme, California, three concepts of fixed bottom stations were proposed. These studies defined the most suitable configurations and power supplies for a manned underwater station capable of supporting the requirements of five individuals, both in life support systems and laboratory spaces. Personnel could remain in the station at depths down to 6,000 ft for 30 days. The three concepts were proposed by General Dynamics Corporation, Groton, Connecticut, Southwest Research Institute, San Antonio, Texas; and Westinghouse Electric Corporation, Baltimore, Maryland. The General Dynamics version is shown here. The station would provide an atmospheric environment in which men could live and perform oceanographic research via remote control sensors, instruments, and manipulators.

FIGURE IV-11 BASIC ALTERNATIVE TO MAN-IN-THE-SEA SYSTEM III — MANNED FIXED BOTTOM STATION

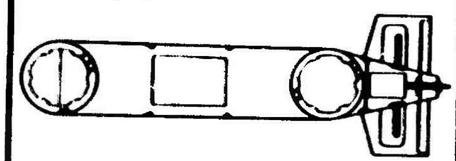
CONFIGURATION	CHARACTERISTICS	DESCRIPTION
SEA DRONE I 	DEPTH 20,000 ft LIFE SUPPORT None SPEED RANGE DIMENSIONS Length 13 ft Width 2 ft PAYLOAD 135 lb CREW None	The SEA DRONE unmanned submersible, adaptable for a variety of oceanographic missions, is currently being developed by Oceanic Industry, Inc., at Seattle, Washington. It is a device developed entirely with existing components and will be controlled acoustically at ranges up to 6 nmi. It can be instrumented for scientific measurements—sound velocity, salinity, temperature, acoustic profiling, water chemistry, etc.; rigged with cameras for underwater mapping, reconnaissance and search, or equipped with a proton magnetometer to locate mineral deposits or metal objects such as sunken ships, mines, or underwater installations.

FIGURE IV-12 BASIC ALTERNATIVE TO MAN-IN-THE-SEA SYSTEM IV — UNMANNED FREE SWIMMING VEHICLE

CONFIGURATION	CHARACTERISTICS	DESCRIPTION
CURV 	DEPTH 2,000 ft LIFE SUPPORT None SPEED 2 3 kt RANGE Unlimited DIMENSIONS Length 13 ft, Width 5 ft, Height 6 ft PAYLOAD 2,000 lb CREW None	CURV (cable controlled underwater research vehicle) was developed by the U.S. Naval Ordnance Test Station, Pasadena, California. CURV weighs about 1 ton and operates to depths of about 2,000 ft. Advanced versions should be able to reach 6,000 ft, however. The vehicle was designed to recover torpedos and other hardware weighing a maximum of 1 ton. The CURV vehicle is operated by a five-man crew on the surface. This crew directs, controls, and monitors recovery operation through a closed circuit television network, supported by acoustic detection and positioning components.

CONFIGURATION	CHARACTERISTICS	DESCRIPTION
 MOBOT  UNUMO	DEPTH 1,000 ft LIFE SUPPORT None SPEED 2 3 kt RANGE Unlimited DIMENSIONS Length, Width 6 ft, Height 14 ft PAYLOAD CREW None	The MOBOT (MObile roBOT) was developed by Hughes Aircraft Company and is used by Shell Oil Company of California as an underwater wellhead manipulator. MOBOT consists of an electrohydraulic vehicle designed to be lowered into the ocean, land on a track, and operated to insert or break out screws arranged in a horizontal axis. The MOBOT's operations are directed from the surface by means of a closed circuit television network supported by acoustic sensors. MOBOT, because of the nature of the work it must perform, is very specialized and therefore is limited with respect to the underwater work it can perform. A more advanced version of MOBOT has been proposed but to date has not been constructed. This advanced vehicle, called UNUMO, is also shown here.

FIGURE IV 13 BASIC ALTERNATIVE TO MAN IN THE SEA SYSTEM V UNMANNED TETHERED VEHICLE

V FUNCTIONAL COMPARISON OF ALTERNATIVES

A. General

The functional comparison of alternative systems available to accomplish undersea tasks is directed towards answering the following questions:

1. What are the unique capabilities of the MAN-IN-THE-SEA systems as compared with alternative means of accomplishing undersea tasks?
2. Which Navy undersea missions have essential tasks that require the unique capabilities of MAN-IN-THE SEA systems?

The approach taken to answer the fundamental questions posed above was as follows: First, a set of performance criteria on which to base the functional comparison was defined. Second, identification was made of the functional requirements for each defined mission and operation. Next, a comparative analysis was conducted to identify the unique capabilities of MAN-IN-THE-SEA systems. And finally, the missions and operations with associated tasks that require the unique capabilities of MAN-IN-THE SEA systems were isolated.

B. Performance Criteria

Ten basic criteria were chosen for evaluating functional performance in this study. These criteria are used here to provide a general statement of functional performance requirements, that is, a definition of capabilities required to perform the undersea missions and operations. These same criteria are used as the basis for defining the capabilities of MAN-IN-THE-SEA systems and alternatives. Finally, the defined functional performance requirements and alternative capabilities stated in terms of these ten basic functional performance criteria are used for the comparative analysis of alternatives.

The ten basic functional performance criteria are: depth, time, mobility, load carrying, maneuverability, manipulation, sensing, cognition, hardness, and covertness. The first two--depth and time--have been the primary performance criteria used in the past to assess and select alternative systems for mission performance. However, in the analysis conducted during this study, simple, depth-time statements of requirements and capabilities were not adequate, as will become clear in the comparative analysis. Each of the defined basic performance criteria and its major considerations are given in the following:

<u>Depth</u>. The depth criterion is concerned with: (1) the mean depth requirement for projected functional operation, (2) the the maximum depth capability of an alternative system, and (3) the excursion depth requirements of an operation and the excursion depth capability of alternative systems. Excursion depth means the depth range variation about the required mean operating depth and the depth range capability of alternative systems.

<u>Time</u>. The time criterion is concerned with: (1) the time required to complete a projected functional operation, and (2) the reaction time requirement and the reaction time capability of alternative systems. The reaction time is the time required to move from staging point to job site.

<u>Mobility</u>. The mobility criterion is concerned with: (1) the speed of motion required to complete a projected functional operation and the speed capability of the alternative system, and (2) the range coverage required to complete a projected functional operation and the range capability of the alternative systems. In some instances, speed-range criteria might be combined to form the single criterion of endurance requirement of capability. In addition to the speed criterion, which generally refers to horizontal motion, it is necessary to add the vertical rate of motion as a mobility criterion for the statement of requirements and capabilities.

Load Carrying. The load carrying criterion is concerned with: (1) the size and weight of the object that must be transported to satisfy a projected functional operation, and (2) the size and weight that alternative systems are capable of carrying.

Maneuverability. The maneuverability criterion is concerned with: (1) the access limits associated with a projected functional operation and the ability of a system to reach tight spaces, and (2) the degree of freedom available in each of the alternative systems.

Manipulation. The manipulation criterion is concerned with all motions and applied forces that are associated with hand, arm, and shoulder actions of man in accomplishing work. A representation division of manipulative criterion is the statement of degree of skill required to accomplish a given task. For the purposes of this study manipulative measures are divided into minimum, moderate, and complex skill levels.

Sensing. The sensing criterion is concerned with: (1) the visual, acoustic, electromagnetic, and tactile senses required to accomplish functional operations, and (2) the capabilities of alternative systems for meeting these requirements.

Cognition. The cognition criterion refers specifically to: (1) the cognitive skills required to make an on-site assessment of a given functional operation, and (2) the on-site assessment capability of the alternative systems.

Hardness. The hardness criterion is concerned with: (1) the resistance requirement to hazards, such as explosion, nuclear radiation, temperature, and marine life during the accomplishment of projected functional operations, and (2) the resistance capability of alternative systems to hazards.

Covertness. The covertness criterion is concerned with: (1) the required resistance to detection by visual, acoustic, magnetic, and electrical sensors during the accomplishment of a projected functional operation, and (2) the ability of alternatives to avoid detection by the various sensors.

C. Performance Requirements

The mission, operation, and generalized tasks relationships are the basis for the development of the performance requirements matrix shown in Table V-1. The performance requirements shown in this table are

Table V-1

MISSIONS, OPERATIONS, AND FUNCTIONAL REQUIREMENTS MATRIX

- H = hours
- D = days
- a = less than 100 nmi
- b = very short, operation independent of range
- ℓ = large
- s = small
- W_W = world wide
- 1 = very important to success
- 2 = important to success
- 3 = not too important to success
- 4 = unimportant to success

Planning Objectives																																								
Planning Documents					Strike WARFARE								Antisubmarine Warfare							Command Support								Operational Support									Depth		Time	
NSS Naval Strategic Studies	NMRG Naval Mid-Range Guidance	NMLG Naval Long Range Guidance	MRO Naval Mid-Range Objectives	NSP Naval Support Plan	11 Airborne Attack	12 Surface Attack	13 Submarine Attack	14 Amphibious Assault	15 Strategic Deterrence	16 Airborne Anti Air	17 Surface Anti Air	18 Vacant	21 Airborne ASW	22 Surface ASW	23 Submarine Surveillance	24 Undersea Surveillance	25 Mining	26 Mine Countermeasures	27 ASW Ancillary Support	31 Command Control	32 Naval Communications	33 Electronic Warfare	34 Navigation	35 Ocean Surveillance	36 Reconnaissance and Inte	37 Environmental Systems	38 Special Warfarc	41 Logistics	42 Vacant	43 Personnel	44 Astronautic Support	45 Aviation Support	46 Ship Support	47 Ordnance Support	37 NBC Defense	UNDERSEA FUNCTIONAL OPERATIONS	Mean depth	Excursion depth	Travel time	Duration of operation
																			13								15			1			*			**Surveillance**				
																																				• Landing beach area	200		H	H_D
																																				• Enemy harbor	200		H	H_D
																																				• U.S. harbor protection	200		H	D
																																				• Inshore USW	< 600		H	D
																												2								• USW all ranges and depths	All			D
																			13								15			1			*			**Reconnaissance**				
																																				• Beach area	200		H_D	H_D
																																				• Enemy harbor	200		H_D	H_D
																																				• Mining environment	200		H_D	H_D
																			13											1			3,4 8,9			**Mining**				
																																				• Mine hunting and countermeasures	< 600		H	D
																																				• Mine plants	1000		H	H
																																				• Disarm mine	< 600		H	H
																																				• Interrogate mine fields	< 600		H	D
																							14					2					3,4			**Navigation Surveys**				
																												2		1			†			**Recovery**				
																																	16			• Small objects	2000		H	D
																																				• Torpedoes	2000		H	D
																																				• Nuclear weapons	2000		H	D
																																				• Space hardware	2000		H	D
																																	6			• Large objects	2000		H	D
																												2		1			3,4 18			**Facility Installations**				
																																				• Sonar array	d		D	
																																		17		• Bottom mounted ULM	2000		D	
																																				• Navigation markers	2000		H	
																																				• Cable laying and inspection	d		H	
																																				• General construction	2000		D	
																												2		1			3,4 5			**Salvage**				
																																				• Ships	2000		D	
																																				• Aircraft	2000		D	
																												1					3			**Repairs**				
																																				• In port	100		D	
																																				• Underway	100		H_D	
																												2					3,4 5,18			**Support**				
																																				• Oceanographic	All		D	
																																				• Sub rescue personnel	< 600			
																																				• Undersea logistics	< 600		H_D	
																												2		1			3,4 18			**Habitat Development**				

* 2, 3, 7, 8, 13

† 2, 4, 10, 13, 18

Note: Numbers in boxes, above refer to the Reference Requirements first given in the classified addendum to this report

H

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Table V-1

NS, OPERATIONS, AND FUNCTIONAL REQUIREMENTS MATRIX

H = hours
D = days
a = less than 100 nmi
b = very short, operation independent of range
ℓ = large
s = small
W_W = world wide
1 = very important to success
2 = important to success
3 = not too important to success
4 = unimportant to success

			Operational Support									Functional Performance Requirements: Depth		Time		Mobility			Load Carrying		Maneuverability		Manipulation			Sensing				COGNITION	Hardness				Covertness			
36 Reconnaissance and Inte	37 Environmental Systems	38 Special Warfare	41 Logistics	42 Vacant	43 Personnel	44 Astronautic Support	45 Aviation Support	46 Ship Support	47 Ordnance Support	37 NBC Defense	UNDERSEA FUNCTIONAL OPERATIONS	Mean depth	Excursion depth	Travel time	Duration of operation	Speed	Range	Endurance	Object size	Object weight	Access limit	Degree of freedom	Minimum skills	Moderate skills	Complex skills	Visual	Acoustic	Electromagnetic	Tactile	On scene assessment	Mechanical	Radiation	Temperature	Marine life	Visual	Acoustic	Magnetic	Electrical
		15			1			•			**Surveillance**																											
											• Landing beach area	200		H	H_D	3	a	2	s	s						✓	✓		✓	✓	✓		✓	✓	✓	✓	✓	✓
											• Enemy harbor	200		H	H_D	3	a	2	s	s						✓	✓	✓		✓	✓		✓	✓	✓	✓	✓	✓
											• U.S. harbor protection	200		H	D	3		2	s	s										✓			✓	✓				
											• Inshore USW	<600		H	D	2		2	s	s						✓	✓	✓		✓	✓		✓	✓	✓	✓	✓	✓
			2								• USW all ranges and depths	All			D												✓			✓	✓		✓	✓	✓	✓	✓	✓
		15			1			•			**Reconnaissance**																											
											• Beach area	200		H_D	H_D	3	a	1	s	s						✓	✓		✓	✓			✓	✓	✓	✓	✓	✓
											• Enemy harbor	200		H_D	H_D	3	a	1	s	s						✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓
											• Mining environment	200		H_D	H_D	3	a	1	s	s							✓	✓		✓			✓	✓	✓	✓	✓	✓
					1			3,4 8,9			**Mining**																											
											• Mine hunting and countermeasures	<600		H	D	2	s	2	s	s			✓			✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓
											• Mine plants	1000		H	H	2		2	s	s			✓			✓	✓				✓		✓	✓				
											• Disarm mine	<600		H	H	3	s	2	s	s			✓	✓	✓	✓				✓	✓		✓	✓	✓	✓	✓	✓
											• Interrogate mine fields	<600		H	D	2	s	2	s	s			✓			✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓
			2					3,4			**Navigation Surveys**																											
			2		1			•			**Recovery**																											
								16			• Small objects	2000		H	D	3	b	2	BB	5T			✓			✓	✓	✓	✓	✓								
											• Torpedoes	2000		H	D	3	b	2	s	s			✓			✓	✓	✓	✓	✓	✓		✓	✓		✓	✓	✓
											• Nuclear weapons	2000		H	D	3	b	2	s	s			✓			✓	✓	✓	✓	✓		✓	✓	✓				
											• Space hardware	2000		H	D	3	b	2	ℓ	ℓ			✓			✓	✓	✓	✓	✓		✓	✓	✓				
								6			• Large objects	2000		H	D	3	b	2	Sub	1000 T			✓	✓	✓	✓	✓	✓	✓	✓			✓	✓				
			2		1			3,4 18			**Facility Installations**																											
											• Sonar array	d		D		3	b	2	s	s	✓		✓	✓	✓	✓			✓	✓			✓	✓				
									17		• Bottom mounted ULM	2000		D		3	b	2	s	s	✓		✓	✓	✓	✓			✓	✓			✓	✓	✓	✓	✓	✓
											• Navigation markers	2000		H		3	b	2	s	s			✓			✓	✓	✓	✓	✓			✓	✓				
											• Cable laying and inspection	d		H		3	b	2	s	s			✓	✓		✓			✓	✓			✓	✓	✓	✓	✓	✓
											• General construction	2000		D		3	b	2	s	s	✓		✓	✓	✓	✓			✓	✓			✓	✓				
			2		1			3,4 5			**Salvage**																											
											• Ships	2000		D		3	b	2	ℓ	[illegible]	✓		✓	✓	✓	✓			✓	✓			✓	✓				
											• Aircraft	2000		D		3	b	2	ℓ	[illegible]	✓		✓	✓	✓	✓			✓	✓			✓	✓				
			1					3			**Repairs**																											
											• In port	100		D		4	b	3					✓	✓	✓	✓			✓	✓			✓	✓				
											• Underway	100		H_D		3	b	3					✓	✓	✓	✓			✓	✓			✓	✓				
			2					3,4 5,18			**Support**																											
											• Oceanographic	All		D		3	b	3	s	s			✓			✓	✓		✓	✓			✓	✓	✓	✓	✓	✓
											• Sub rescue personnel	<600				2	b	1	ℓ	ℓ			✓	✓	✓	✓	✓		✓	✓			✓	✓				
											• Undersea logistics	<600		H_D		3	b	3	s	s			✓			✓	✓		✓	✓			✓	✓	✓	✓	✓	✓
			2		1			3,4 18			**Habitat Development**				4	b	1						✓	✓	✓	✓	✓		✓	✓			✓	✓				

*Requirements first given in the

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V-5

D

Table V-1 (Concluded)

MISSIONS, OPERATIONS, AND FUNCTIONAL REQUIREMENTS MATRIX

H = hours
D = days
a = less than 100 nmi
b = very short, operation independent of range
ℓ = large
s = small
W_W = world wide
1 = very important to success
2 = important to success
3 = not too important to success
4 = unimportant to success

Operational Doctrine

UNDERSEA FUNCTIONAL OPERATIONS	NWP 11-A Naval Operational Planning	NWP 22-A Doctrine for Amphibious Operations	NWIP 22-1B The Amphibious Task Force Plan	NWIP 22-4A UDT in Amphibious Operations	NWIP 23-1B Submarine Primary Missions	NWIP 23-2B Submarine Support Operations	NWIP 23-9A Submarine Evasion Manual	NWP 24-B ASW Operations	NWIP 24-1A ASW Classification Manual	NWP 26-A Mining Operations	NWIP 26-1 Minefield Planning	NWIP 27-A Mine Countermeasures Operations	NWIP 27-1A Support to Mine Countermeasures Operations	NWIP 27-2 Mine Hunting Procedures	NWP 28-A Nuclear Warfare Operations	NWIP 29-1 Seal Teams in Naval Special Warfare	USN ADD 37-A Submarine Disaster SAR Operations	NWP 37-A National SAR Manual	USN Add 27A Submarine Disaster SAR Operations	SUPP 37-A Wartime SAR Procedures	NWP 38-B Replenishment at Sea	NWP 39-A Base Defense	NWP 40-A Harbor Defense
Surveillance																							
• Landing beach area		√		√	√	√				√	√	√	√				√						
• Enemy harbor		√		√	√	√				√	√						√						
• U.S. harbor protection										√	√	√	√										√
• Inshore USW		√		√				√		√	√						√						√
• USW all ranges and depths								√															
Reconnaissance																	√						
• Beach area		√		√	√	√				√	√	√	√				√						
• Enemy harbor		√		√	√	√				√	√	√	√				√						
• Mining environment		√		√	√	√				√	√	√	√										
Mining										√													
• Mine hunting and countermeasures		√		√								√	√	√									√
• Mine plants		√				√				√	√												√
• Disarm mine				√							√	√											√
• Interrogate mine fields											√	√	√										√
Navigation surveys																							
Recovery																							
• Small objects																							
• Torpedoes																							
• Nuclear weapons				√																			
• Space hardware																							
• Large objects																							
Facility Installations																							
• Sonar array								√															
• Bottom mounted ULM																							
• Navigation markers																							
• Cable laying and inspection								√															
• General construction																							
Salvage																							
• Ships																							
• Aircraft																							
Repairs																							
• In port																							
• Underway																							
Support																							
• Oceanographic		√	√	√	√	√		√		√	√	√	√	√		√	√					√	√
• Sub rescue personnel																					√		
• Undersea logistics		√	√	√	√			√								√						√	
Habitat Development																							

Functional Perform

UNDERSEA FUNCTIONAL OPERATIONS	Depth: Mean depth	Depth: Excursion depth	Time: Travel time	Time: Duration of operation	Mobility: Speed	Mobility: Range	Mobility: Endurance	Load carrying: Object size	Load carrying: Object weight	Maneuverability: Access limit	Maneuverability: Degree of freedom	Manipulation: Minimum skills	Manipulation: Moderate skills
Surveillance													
• Landing beach area	200		H	H_D	3	a	2	s	s				
• Enemy harbor	200		H	H_D	3	a	2	s	s				
• U.S. harbor protection	200		H	D	3		2	s	s				
• Inshore USW	< 600		H	D	2		2	s	s				
• USW all ranges and depths	All			D									
Reconnaissance													
• Beach area	200		H_D	H_D	3	a	1	s	s				
• Enemy harbor	200		H_D	H_D	3	a	1	s	s				
• Mining environment	200		H_D	H_D	3	a	1	s	s				
Mining													
• Mine hunting and countermeasures	< 600		H	D	2	a	2	s	s			√	
• Mine plants	1000		H	H	2		2	s	s			√	
• Disarm mine	< 600		H	H	3	a	2	s	s			√	√
• Interrogate mine fields	< 600		H	D	2	a	2	s	s			√	
Navigation surveys													
Recovery													
• Small objects	2000		H	D	3	b	2	BB	5T			√	
• Torpedoes	2000		H	D	3	b	2	s	s			√	
• Nuclear weapons	2000		H	D	3	b	2	s	s			√	
• Space hardware	2000		H	D	3	b	2	ℓ	ℓ			√	
• Large objects	2000		H	D	3	b	2	Sub	1000 T			√	√
Facility Installations													
• Sonar array	d		D		3	b	2	s	s	√		√	√
• Bottom mounted ULM	2000		D		3	b	2	s	s	√		√	√
• Navigation markers	2000		H		3	b	2	s	s			√	
• Cable laying and inspection	d		H		3	b	2	s	s			√	√
• General construction	2000		D		3	b	2	s	s	√		√	√
Salvage													
• Ships	2000		D		3	b	3	ℓ	√	√		√	√
• Aircraft	2000		D		3	b	3	ℓ	√	√		√	√
Repairs													
• In port	100		D		4		3					√	√
• Underway	100		H_D		3	b	3					√	√
Support													
• Oceanographic	All		D		3	b	3	s	s			√	
• Sub rescue personnel	< 600		H_D		2	b	1	ℓ	ℓ			√	√
• Undersea logistics	< 600		H_D		3	b	3	s	s			√	
Habitat Development					4	b	1					√	√

* 3, 4, 8, 9, 13
• 3, 4, 10, 13, 18

Note: Numbers in boxes, above refer to the Reference Requirements first given in the classified addendum to this report

A

Table V-1 (Concluded)

MISSIONS, OPERATIONS, AND FUNCTIONAL REQUIREMENTS MATRIX

H = hours
D = days
a = less than 100 nmi
b = very short, operation independent of range
ℓ = large
s = small
W_W = world wide
1 = very important to success
2 = important to success
3 = not too important to success
4 = unimportant to success

ctrine											Functional Performance Requirements																										
											Depth		Time		Mobility			Load carrying		Maneuverability		Manipulation			Sensing				Cognition	Hardness				Covertness			
NWIP 27-2 Mine Hunting Procedures	NWIP 28-A Nuclear Warfare Operations	NWIP 29-1 Seal Teams in Naval Special Warfare	USN ADD 37-A Submarine Disaster SAR Operations	NWP 37-A National SAR Manual	USN Add 27A Submarine Disaster SAR Operations	SUPP 37-A Wartime SAR Procedures	NWP 38-B Replenishment at Sea	NWP 39-A Base Defense	NWP 40-A Harbor Defense	UNDERSEA FUNCTIONAL OPERATIONS	Mean depth	Excursion depth	Travel time	Duration of operation	Speed	Range	Endurance	Object size	Object weight	Access limit	Degree of freedom	Minimum skills	Moderate skills	Complex skills	Visual	Acoustic	Electromagnetic	Tactile	On scene assessment	Mechanical	Radiation	Temperature	Marine life	Visual	Acoustic	Magnetic	Electrical
										Surveillance																											
			√							• Landing beach area	200		H	H_D	3	a	2	s	s						√	√		√	√	√		√	√	√	√	√	√
			√							• Enemy harbor	200		H	H_D	3	a	2	s	s						√	√	√		√	√		√	√	√	√	√	√
									√	• U.S. harbor protection	200		H	D	3		2	s	s										√			√	√				
			√						√	• Inshore USW	<600		H	D	2		2	s	s						√	√	√		√	√		√	√	√	√	√	√
										• USW all ranges and depths	All			D												√			√	√		√	√	√	√	√	√
			√							**Reconnaissance**																											
			√							• Beach area	200		H_D	H_D	3	a	1	s	s						√	√		√	√			√	√	√	√	√	√
			√							• Enemy harbor	200		H_D	H_D	3	a	1	s	s						√	√	√		√	√	√	√	√	√	√	√	√
										• Mining environment	200		H_D	H_D	3	a	1	s	s							√	√		√			√	√	√	√	√	√
										Mining																											
									√	• Mine hunting and countermeasures	<600		H	D	2	a	2	s	s			√			√	√	√	√	√	√		√	√	√	√	√	√
									√	• Mine plants	1000		H	H	2		2	s	s			√			√	√				√		√	√				
									√	• Disarm mine	<600		H	H	3	a	2	s	s			√	√	√	√				√	√		√	√	√	√	√	√
									√	• Interrogate mine fields	<600		H	D	2	a	2	s	s			√			√	√	√	√	√	√		√	√	√	√	√	√
										Navigation surveys																											
										Recovery																											
										• Small objects	2000		H	D	3	b	2	BB	5T			√			√	√	√	√	√								
										• Torpedoes	2000		H	D	3	b	2	s	s			√			√	√	√	√	√	√		√	√		√	√	√
										• Nuclear weapons	2000		H	D	3	b	2	s	s			√			√	√	√	√	√		√	√	√				
										• Space hardware	2000		H	D	3	b	2	ℓ	ℓ			√			√	√	√	√	√		√	√	√				
										• Large objects	2000		H	D	3	b	2	Sub	1000 T			√	√	√	√	√	√	√	√			√	√				
										Facility Installations																											
										• Sonar array	d		D		3	b	2	s	s	√		√	√	√	√			√	√			√	√				
										• Bottom mounted ULM	2000		D		3	b	2	s	s	√		√	√	√	√			√	√			√	√	√	√	√	√
										• Navigation markers	2000		H		3	b	2	s	s			√			√	√	√	√	√			√	√				
										• Cable laying and inspection	d		H		3	b	2	s	s			√	√		√			√	√			√	√	√	√	√	√
										• General construction	2000		D		3	b	2	s	s	√		√	√	√	√			√	√			√	√				
										Salvage																											
										• Ships	2000		D		3	b	2	ℓ	√	√		√	√	√	√			√	√			√	√				
										• Aircraft	2000		D		3	b	2	ℓ	√	√		√	√	√	√			√	√			√	√				
										Repairs																											
										• In port	100		D		4		3					√	√	√	√			√	√			√	√				
										• Underway	100		H_D		3	b	3					√	√	√	√			√	√			√	√				
										Support																											
√		√	√					√	√	• Oceanographic	All		D		3	b	2	s	s			√			√	√		√	√			√	√	√	√	√	√
							√			• Sub rescue personnel	<600		H_D		2	b	1	ℓ	ℓ			√	√	√	√	√		√	√			√	√				
		√						√		• Undersea logistics	<600		H_D		3	b	3	s	s			√			√	√		√	√			√	√	√	√	√	√
										Habitat Development					4	b	1					√	√	√	√	√		√	√			√	√				

...ces, above refer to the Reference Requirements first given in the ...ddendum to this report subjective estimates of future requirements. They are qualitative statements that tend to set the boundaries for requirements rather than specific quantitative statements of those requirements. The latter can be arrived at only through a comprehensive mission and functional operations analysis. Such a comprehensive analysis of each operation was not deemed necessary in this study.

In relating the missions and operations to a particular subcategory of the performance requirements, some general interpretations were made of the particular requirements of depth, travel time, duration of operation, speed, range, endurance, object size, and object weight. In all other descriptions of performance requirements, a check in the appropriate row and column of the Operation and Performance Requirement Matrix indicates only that the particular operation is supported by the indicated functional requirement. Such requirements as travel time and mission duration time are estimated to be in the order of hours or days. Speed and endurance requirements are estimated on a graduated number scale, where 1 is very important to success, 2 and 3 are less important, and 4 is very unimportant. Range is estimated in two ways: (1) the range is less than 100 nautical miles (nmi) or (2) the range is relatively short, i.e., the operation is independent of range. Reference 1* provides an assessment of ranges under 100 nmi for particular strike warfare operations in those world areas where reconnaissance and surveillance are more probable. Using these ranges, it was computed that, in 80% of the areas, the range from the 33-fathom line (200 ft) to the beach is 40 nmi or less. In 50% of the areas, 10 nmi or less is the range to the 33-fathom line. With respect to the object weight and size under load carrying ability, only two categories for estimated weight are used: small, which is 5 tons or less, and large, which is 10 tons or greater.

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* See Section VII for references.

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D. Comparative Analysis

The spectrum of available undersea work system alternatives described in Section IV serves as the basis for the comparative analysis of system capabilities. Since the described system alternatives reflect current capabilities, whereas this study addresses the 1975-85 era, the project team had to project the future capabilities. Therefore, in the comparative analysis that follows, current R&D efforts are reviewed briefly and their effects on future systems capabilities are assessed.

DEPTH CAPABILITY

Summary

Even by the most optimistic estimates, the depth capability of MAN-IN-THE-SEA systems is very limited relative to that of alternative work system approaches. Conservative estimates of man's physiological depth limits are 1,250-1,500 ft. The most optimistic estimates place the limit at about 3,000 ft.

Technological and physiological factors limit the depth an unshielded man can reach (see Appendix B). There may be some psychological limits as well, but they are considered to be secondary in importance.

The principal technological factors affecting man's depth capability are: (1) the limitations in life support equipment, and (2) the limited ability to control and monitor critical mixed gas breathing atmospheres. The first limitation constrains the depth that a free swimmer can reach and still have sufficient endurance to accomplish useful work. The present solution to this limitation is the use of the tethering technique, in which man is connected by a hose to a larger gas supply on the surface, on a vehicle, or in a bottom station. The problem of limited gas supply might be overcome by such concepts as cryogenic gas storage and the extraction of oxygen from seawater (artificial gills). Development of improved gas analysis techniques would overcome the second technological limitation on depth.

The physiological factors that limit the depth to which man can descend stem from the indirect and direct effects of hydrostatic pressure. The principal indirect effects of pressure are increased gas density, oxygen toxicity, and inert gas toxicity effects in breathing. As gas density increases with increased pressure (depth), the effort required to breathe increases proportionally. It is quite conceivable that this effort would be equal to a significant amount of man's work output. A technological solution to the gas density problem would be to provide a breathing pump or active ventilation assistance. While the biochemical effects that lead to oxygen toxicity are still not clearly understood, they can be minimized by careful control of the oxygen content in the breathing environment. This control is a technological factor mentioned earlier. As with oxygen toxicity, the exact biochemical effects resulting in inert gas toxicity are not understood. The current solution to reducing the effects of inert gas toxicity is to use multiple gas mixtures, helium-nitrogen-oxygen, and even hydrogen in the breathing mixtures. The fluid breathing concept currently being explored is a very intriguing solution to the inert gas toxicity problem. In this concept, oxygen enriched fluid is used to fill the lungs, this eliminating the need for inert gas. While this concept is still in a very early research stage, successful tests have been made with animals.* The direct effects of pressure on the cellular structure of the human body also limit the depth that man is able to endure. Although data are not available on human cellular tolerance to pressure, some effects of pressure on human skeletal structure have been indicated, and some early experiments on animals have indicated that pressure affects the central nervous system. Looseness of joints at depths exceeding 500 ft has been reported; divers' arms and legs slip out of joint rather easily at these depths. At depths greater than 1,000 ft, there appear to be some effects on the cellular

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* Recent unconfirmed reports indicate that human volunteers have been used in successful experiments in which half the lung was filled with fluid.

structures. It has been demonstrated that the direct effects of pressure include: (1) failure of cell division, (2) failure of ameboid movement, (3) inhibition of biological luminescense, and (4) inhibition of growth of bacteria. Bacterial growth is inhibited by the pressures at 1,000 ft of seawater. To date, man has reached a depth of slightly over 1,000 ft. It is important to note that there is no information on the long term effects of inhibited bacterial growth at these depths. Conservative estimates of physiologists who have worked with diving technology place man's depth limit from 1,250 ft to 1,500 ft. The most optimistic estimates place the limit at about 3,000 ft.

In addition to the maximum depth limit, a diver is limited in his ability to vary depth during the work cycle. This limitation is imposed by the need for decompression (see Appendix B). The actual excursion depth limit during a working dive is still not well defined and is being investigated by physiologists.

Compared with MAN-IN-THE-SEA concepts, even the current operating vehicles have exceeded, by a factor of 2, the most optimistic estimate of unshielded man's depth limit. In many cases, the depth that a vehicle system can achieve is limited only by economic considerations. With the exception of the BEAVER MARK IV--which was designed to satisfy the requirements of off-shore oil operations and is capable of achieving only a depth of 2,000 ft--most free vehicles are designed for depths around 6,000 ft. A 6,000-ft depth capability allows these vehicles to reach about 30% of the ocean's bottom. Vehicles that are capable of penetrating the deepest ocean depths are in existence, and more advanced and versatile vehicles are being designed and constructed. Tethered vehicles, such as MOBOT, are generally limited by tether length. An advanced design CURV is being developed that can approach 6,000 ft.

TIME CAPABILITY

Summary

Time capability of MAN-IN-THE-SEA concepts is comparable to the vehicle oriented systems with the following qualifications. More must be known about the long term physiological effects of high hydrostatic pressure. Water immersion time for MAN-IN-THE-SEA should be unlimited if adequate protective dress can be provided; this factor does not appear to be a technological limitation.

The time capability of MAN-IN-THE-SEA concepts is described in terms of total bottom time and water immersion time. Since the development of the saturation diving technique the time a man can stay in ambient pressure, i.e., the bottom time, has increased by several orders of magnitude. A primary objective of research efforts, such as the Navy's SEALAB operations, is to determine the exact length of time that man can exist in a hydrostatic pressure environment. Long terms effects of prolonged exposure to high hydrostatic pressure are practically unknown at this time. In the few experiments to date, no ill effects have been apparent. The depth-time relationships of long term undersea habitation experiments, both completed and planned, are summarized in Fig. V-1.

Water immersion time refers to the length of time a diver actually spends in the water, which is limited primarily by water temperature and the effects of water on human skin. The first, the effects of water temperature, can be avoided by providing heated diving suits for divers. A nuclear-isotope powered, hot water heated suit will be tested during the SEALAB III operations. There should be no water immersion time limit for a diver who is provided with a heated suit. The effects of prolonged water immersion on human skin is under study. Although no data on

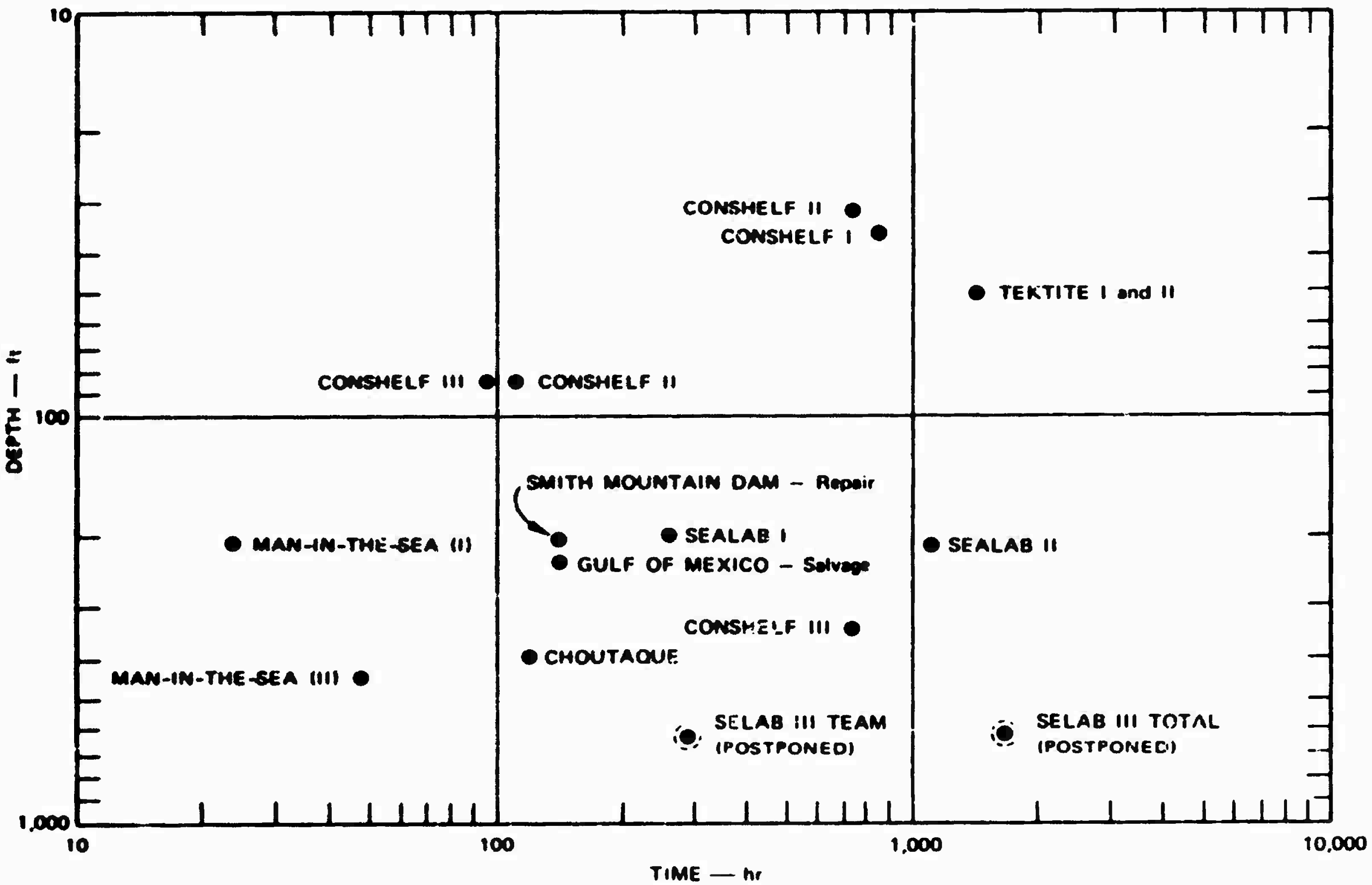

FIGURE V-1 COMPLETED AND PLANNED PROLONGED SUBMERGENCE EXPERIMENTS immersion limits have been found, it would appear that man's capability to withstand immersion could be enhanced by surrounding him with a protective fluid.

In comparison, it would appear that the time capability of MAN-IN-THE-SEA concepts is comparable to the vehicle oriented systems down to depths approaching 600 ft. More must be known, however, about the long term effects of pressure at greater depths. Immersion time for the unshielded man should be unlimited if adequate protective dress can be provided; this factor does not appear to be a technological limitation. The operating time of free vehicles is limited by life support and power source endurance capabilities. The primary constraint is in the endurance limitation of conventional power sources. A compact nuclear power package would eliminate current vehicle endurance limits. Similarly, fixed bottom habitat is power source limited.

MOBILITY CAPABILITY

Summary

The alternatives to MAN-IN-THE-SEA systems have a distinct mobility advantage.

A comparison of the mobility of free swimming man and free swimming vehicle systems is shown in Fig. V-2. The shaded area in the figure identifies the speed-range capability of a free swimmer propelled by swim fins and carrying life support equipment equivalent to the size of three, 72-ft^3 capacity SCUBA tanks. The upper bound is the endurance capability for a trained athelet. The curve is generated from data published in Ref. 2. In comparison, the published speed-range capability

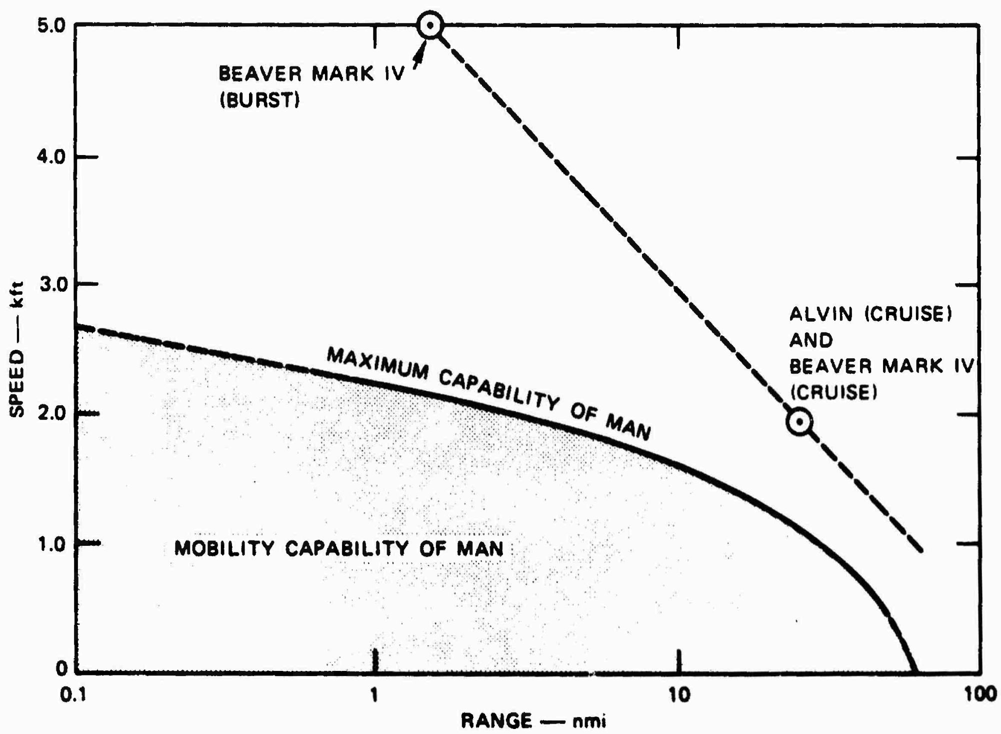

FIGURE V-2 SPEED-RANGE COMPARISON OF MAN AND VEHICLES

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of BEAVER MARK IV and ALVIN are indicated in the figure. The vehicles have a distinct advantage over man. Furthermore, since man's speed-range capability is limited by a physical constraint, whereas the vehicle capabilities are limited by power source technology, the gap between man and vehicle capabilities will increase.

The movements of the tethered man and the tethered vehicles are constrained by the tether. In comparison, however, the tethered vehicles have a distinct mobility advantage over the tethered man because of the propulsion power available to vehicle systems.

LOAD CARRYING CAPABILITY

Summary

On the basis of the in-water weight of loads that must be picked up and transported, vehicle oriented systems will always have an advantage over the man.

A rough estimate of load carrying capability is 20 lb for a man and 2,000 lb for a vehicle, making the vehicle advantage over man a factor of 100. If the comparison is made on the basis of using buoyant lift devices, the vehicle will again have the advantage. This latter advantage is due to the mobility advantage of the vehicle system over the man in transport of a load supported by buoyant lift devices.

MANEUVERING CAPABILITY

Summary

MAN-IN-THE-SEA systems have the advantage over alternative systems in maneuvering capability.

Man's maneuvering capability advantage over the vehicle oriented systems is compared in terms of: (1) the frontal cross sectional area, which is indicative of a system's ability to enter limited access spaces, and (2) the turn radius of the system, which is indicative of a system's ability to maneuver around congested structures. Figure V-3 shows the comparative relationships between MAN-IN-THE-SEA and the spectrum of system alternatives. Clearly, vehicles, manned or unmanned, cannot approach the compactness and agility of man in accomplishing undersea tasks.

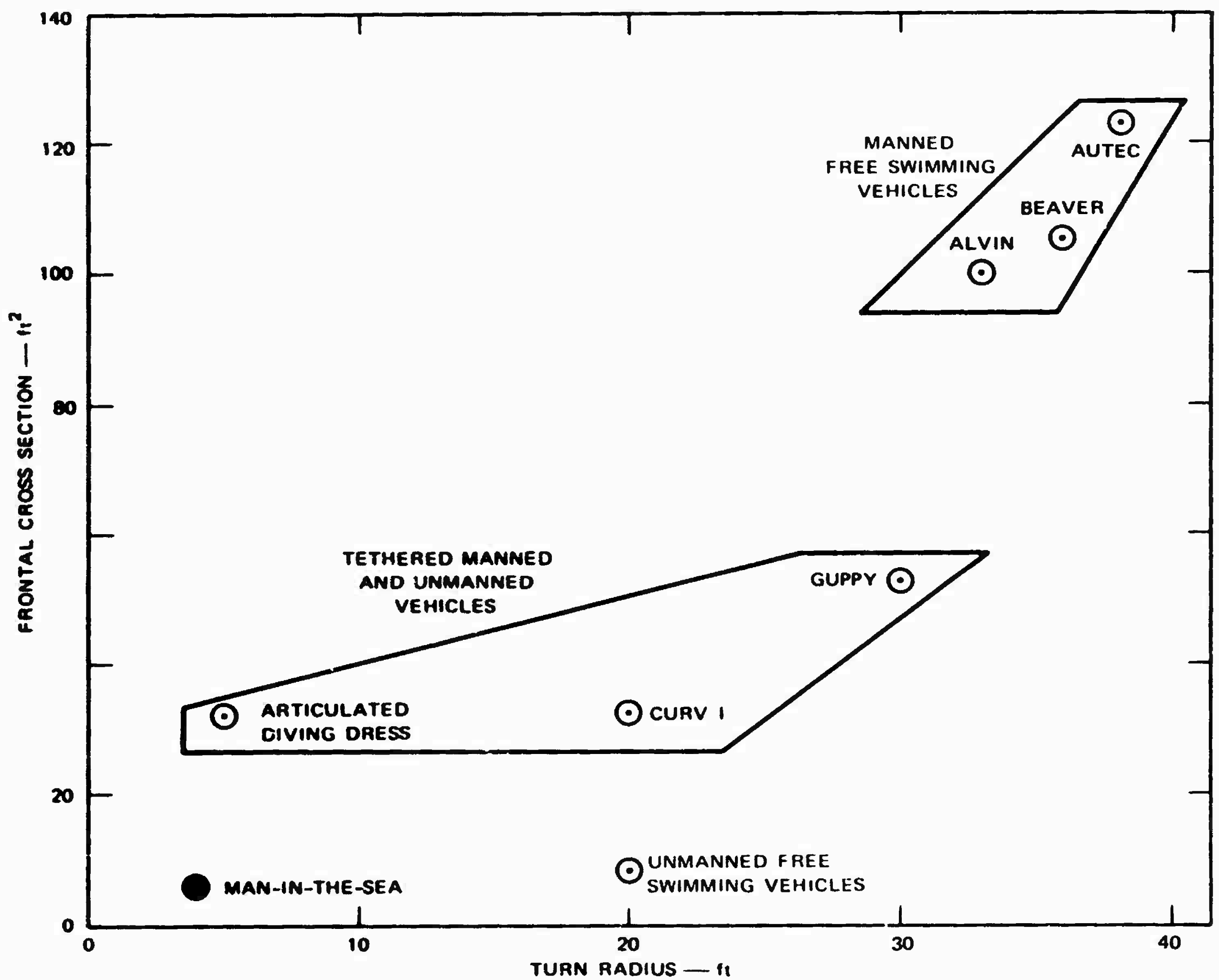

FIGURE V-3 COMPARISON OF THE MANEUVERABILITY OF MAN-IN-THE-SEA SYSTEMS vs TYPICAL SYSTEMS ALTERNATIVES

MANIPULATIVE CAPABILITY

Summary

MAN-IN-THE-SEA systems have a manipulative capability advantage over alternative systems utilizing mechanical manipulators. The advantages are expressed in terms of the dynamic range of man's manipulative capability, his flexibility in handling unexpected manipulative task requirements, and his reliability in task performance.

The comparison of manipulative capabilities of man and mechanical manipulators on vehicles is made difficult by the lack of clearly defined performance measures. There is no quantitative measure of dexterity, nor is there a clear-cut definition of manipulative success or failure. Furthermore, the comparison is complicated by the availability of a wide range of diver tools and mechanical manipulator terminal devices. The comparison made in this study, therefore, is a very general assessment and results in a qualitative statement of manipulative capability.

As the basis for comparing the capabilities of man and mechanical manipulators, the level of manipulative skills required to accomplish specific underwater tasks was defined as shown in Table V-2. A review of available data on diver manipulative performance was conducted and the results are reported in Appendix B. Available descriptive data concerning the capabilities of underwater mechanical manipulators also were reviewed, and a summary is provided in Appendix C. The following conclusions were drawn from the comparison of man and mechanical manipulators:

1. Manipulative tasks that require minimum manipulative skills can be accomplished equally well by man and mechanical manipulators.

Table V-2

SUMMARY OF REQUIRED MANIPULATIVE SKILLS

Manipulative Tasks	Degree of Manipulative Skill Required		
	Minimum	Moderate	Complex
Cutting		■	
• Sawing		■	
• Shearing		■	
• Burning			■
• Pyrotechnics			■
Torqueing		■	
Hammering	■		
Drilling		■	
Punching		■	
Stud driving		■	
• Riveting		■	
• Fastening		■	
Sealing		■	
• Crimping		■	
• Vacuumizing		■	
Welding			■
Coring		■	
Caulking/coating		■	
Guiding/positioning		■	
Connecting/disconnecting	■		
De-embedding	■		
• Raising	■		
• Dislodging	■		
• Excavating	■		

Source: Ref. 2

2. Manipulative tasks that require moderate manipulative skills can be accomplished by man and by a mechanical manipulator if the latter is "given enough time." On the basis of very little data, it is estimated that mechanical manipulators will take 10 to 100 times as long to accomplish a task, depending on its complexity. For example, a simple connecting/disconnecting task might take a man 5 seconds to accomplish, whereas a manipulator will require a minute; a more complex bolting task might take a man 10 seconds and a manipulator 5 minutes.

3. Manipulative tasks that require complex manipulative skills can be accomplished only by man.

For a further comparison, the tools and terminal devices available for accomplishing underwater tasks are listed in Table V-3.

Additional important manipulative advantages of man over the mechanical manipulators are the dynamic range of man's manipulative capability, his flexibility, and his reliability. Dynamic range refers to the size of jobs a man can handle. For example, a man can easily manipulate objects smaller than 0.1 inch to objects up to sizes measured in feet. Various sizes of mechanical manipulators are generally required to handle the range of objects that one man can handle. Flexibility refers to the range of jobs that a man can handle. For example, one man can use an unlimited range of tools compared with the mechanical manipulators (Table V-3). Furthermore, man has the flexibility to use improvised tools on the job site when an unexpected situation arises, whereas mechanical manipulators with specialized terminal devices are not as flexible. Reliability refers to the ability of accomplishing a specific manipulative task without error, for example, dropping components such as nuts, bolts, and even tools, during a job. Although reliability is somewhat difficult to measure, it is generally agreed that man is a much more reliable manipulator than mechanical devices.

Table V-3

AVAILABLE HAND AND MECHANICAL MANIPULATOR TOOLS

Tasks	Saw-powered	Saw-hand	Saw-zero reaction	Shears	Open and box wrenches	Adjustable wrench	Ratchet wrenches	Power wrench-impact	Wrench-zero reaction	Screwdriver	Ratchet screwdriver	Screwdriver-zero reaction	Hammer-hand
Cutting													
• Sawing	x	x	√										
• Shearing				√									
• Burning													
• Pyrotechnics													
Torqueing					x	x	x	√	√	x	x	x	
Hammering													x
Drilling													
Punching													
Stud driving													
• Riveting													
• Fastening													
Sealing													
• Crimping													
• Vacuumizing													
Welding													
Coring													
Caulking/cooling													x
Guiding/positioning													
Connect/disconnecting					x	x	x	√	√	x	x	x	x
De-embedding													
• Raising													
• Dislodging													x
• Excavating													

Tasks	Hammer-magnetomotive	Drill-powered	Drill-hand	Drill-zero reaction	Punch-magnetomotive	Punching head	Riveter-magnetic	Stud gun and fastener	Crimping tool	Vacuum tool	Electron beam gun	Arc/oxygen	Oxygen/hydrogen
Cutting													
• Sawing													
• Shearing													
• Burning													
• Pyrotechnics													
Torqueing													
Hammering	√												
Drilling		√	x	√									
Punching					x	x							
Stud driving													
• Riveting							√	√					
• Fastening							√	√					
Sealing													
• Crimping									√				
• Vacuumizing										√			
Welding											x	x	x
Coring		√	x	√									
Caulking/cooling													
Guiding/positioning													
Connect/disconnecting							√	√			x	x	x
De-embedding													
• Raising		√	x	√			√	√			x	x	x
• Dislodging													
• Excavating													

Tasks	Metal/arc torch	Coring kit	Guide pins	Coupling fasteners	Slings and rigging gear	Clamps	Ice tongs-clam grip	Jacks and levers	Winches and hoist	Nylon line	Levels	Chisels and caulking tools	Levers
Cutting													
• Sawing													
• Shearing													
• Burning	x												
• Pyrotechnics													
Torqueing													
Hammering													
Drilling													
Punching													
Stud driving													
• Riveting													
• Fastening													
Sealing													
• Crimping													
• Vacuumizing													
Welding	x												
Coring		√											
Caulking/cooling												x	
Guiding/positioning			√		√	√		√	√	√	√		√
Connect/disconnecting			√	√	√	√	x		√	√			√
De-embedding													
• Raising				√	√	√	x	√	√	√			√
• Dislodging					√			√				x	√
• Excavating													

Tasks	Manipulators	Brushes	Inflatable bags	Foam guns	Pyrotechnic charge	TV camera	Work gloves and pads	Knife	Illumination kit	Tool kit container	Squalus washer	Probe	Hardlines
Cutting													
• Sawing							x		x	x			
• Shearing							x		x	x			
• Burning							x		x	x			
• Pyrotechnics					x		x		x	x			
Torqueing							x		x	x			
Hammering							x		x	x			
Drilling							x		x	x			
Punching							x		x	x			
Stud driving													
• Riveting							x		x	x			
• Fastening							x		x	x			
Sealing													
• Crimping									x	x			
• Vacuumizing									x	x			
Welding		√					x		x	x			
Coring									x	x			
Caulking/cooling							x		x	x			
Guiding/positioning	x						x		x	x			x
Connect/disconnecting					x		x	x	x	x			
De-embedding													
• Raising	x		√	√			x		x	x			
• Dislodging	x		√		x		x	x	x	x	x	x	x
• Excavating							x					x	

Note: x = hand tools
√ = hand and mechanical manipulator tools

Source: Ref. 3

SENSING CAPABILITY

Summary

The principal sensory advantage of MAN-IN-THE-SEA systems is the availability of man's tactile senses. The visual capability of man in the water (see Appendix B) and that of man in a vehicle are comparable. Because of the larger payload capability of vehicles, which permits the use of acoustic and electromagnetic sensing devices, the vehicles would normally have the advantage in sensory capabilities. The hearing of man in the water shows some spectral degradation, and at higher frequencies (above 3,000 Hz) there is a complete loss of sound localization capability.

COGNITIVE SKILLS

Summary

In the undersea environment the cognitive skills of unshielded man show some degradation, which is attributed to inert gas toxicity and to some extent, to stress imposed by the hostile ocean environment. If inert gas toxicity problems can be resolved through the use of advanced diving techniques, such as fluid breathing, the cognitive skills or on-site assessment capability of unshielded man could be equivalent to that of a man in the protective shell of a vehicle.

HARDNESS

Summary

With respect to hardness, the vehicle oriented systems have the advantage over the MAN-IN-THE-SEA systems for protecting man from mechanical (explosions), radiation, temperature (cold), and marine life hazards.

One defense against the covert operations of the underwater swimmer or a small submersible is the use of explosive charges in the suspected area. The degree of damage or protection can be related to the vehicle and swimmer with the peak overpressure versus range diagram shown on Fig. V-4.

Figure V-4 represents the peak overpressure in pounds per square inch (psi) as a function of range (R) from a TNT charge. Curves representing the pressure from charge weights of 10, 100, and 1,000 lb are provided. The static pressure at various depths corresponding to the peak overpressure in psi is indicated by the heavy horizontal lines drawn for a depth of 200, 400, 800, 1,000, 2,000, 5,000, and 20,000 ft, respectively.

If an underwater swimmer is susceptible to a dynamic overpressure of 200 psi, or if any equipments outboard of a small submersible are designed to operate no lower than 400 ft, then, according to Fig. V-4, a 10-lb TNT charge within about 120 ft, or a 100-lb charge within about 250 ft, will provide protection or vulnerability, depending upon which is required.

It has been stated without any supporting reference or data that the lethal range from an underwater explosion is where the peak overpressure exceeds 200 psi, i.e., 50% of the time the underwater swimmer

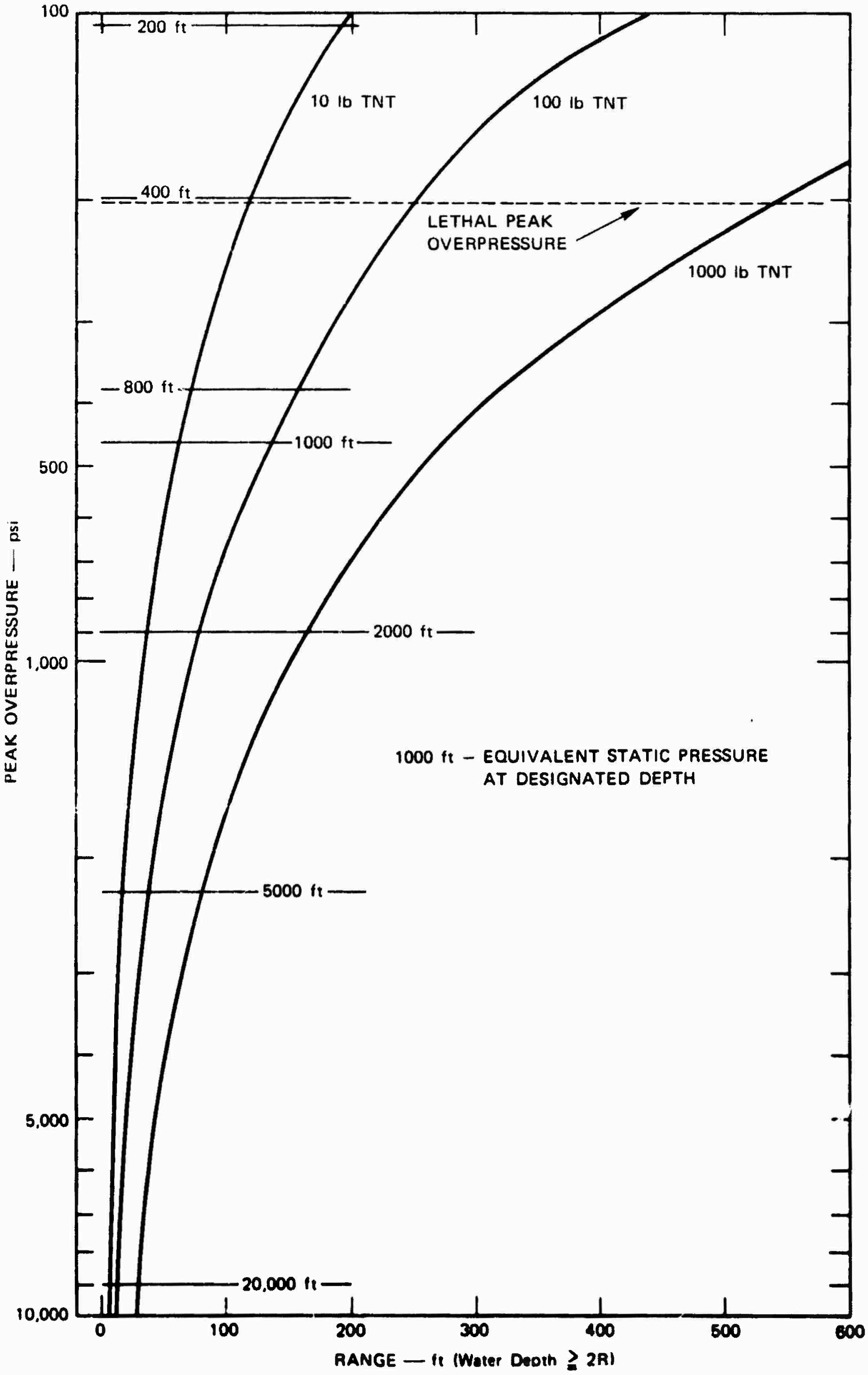

FIGURE V-4 PEAK OVERPRESSURE vs RANGE

will be killed. This 200-psi curve is the dashed curve on Fig. V-4. From these it is evident that 10-lb charges deposited within 100 ft would provide good defense against the swimmer. One can also estimate the lethal range (R_L) with charge weight (W) as follows:

$$R_L = 44 \sqrt[3]{W}$$

where:

R_L = lethal range in ft

W = charge weight in lb of TNT.

Another example from Fig. V-4 is the following. If a small submersible designed to operate at a depth of 1,000 ft is operating near this limit, a 10-lb charge at this depth exploding 150 ft away will create approximately a 150-psi peak overpressure, maybe enough to fail the structure. This too is a definite type of defense or vulnerability.

COVERTNESS

Summary

A free swimming man has the advantage in covertness because of his small size and the availability of equipment to minimize visual, acoustic, magnetic, and electrical sensors. The equipments associated with the tethered man make this system's covertness factor comparable to that of the entire range of vehicle oriented systems.

Passive Acoustic Detection

The small submersible is comparable to a very small battery operated submarine. Except for the NR-1 (nuclear) most all other small submersibles are powered by electric motors. The primary source of noise will be motor, gears, and propeller, assuming no external noise sources and no onboard equipments transmitting noise through the submarine structure. The noise from the propeller, when cavitating, will probably dominate.

Measured noise levels from small submersibles are not available. However, it is reasonable to relate torpedo noise spectrum data with estimated small submersible noise spectrum levels, and then compare these spectrum levels to larger battery-operated conventional submarines. This provides relative spectrum levels for estimating passive detection ranges.

Torpedo noise levels, compared with a quiet submarine, are shown on Fig. V-5. These high noise levels (one and two) are not necessarily indicative of a small submersible. They do indicate, however, how noisy a poorly designed small submersible vehicle for covert operations might be. The quieter noise spectrum (Ref. 4), indicated as three on Fig. V-5, is probably more like the small submersible. From the aspect of quieting the small submersible, five represents a noise spectrum limit that appears attainable.

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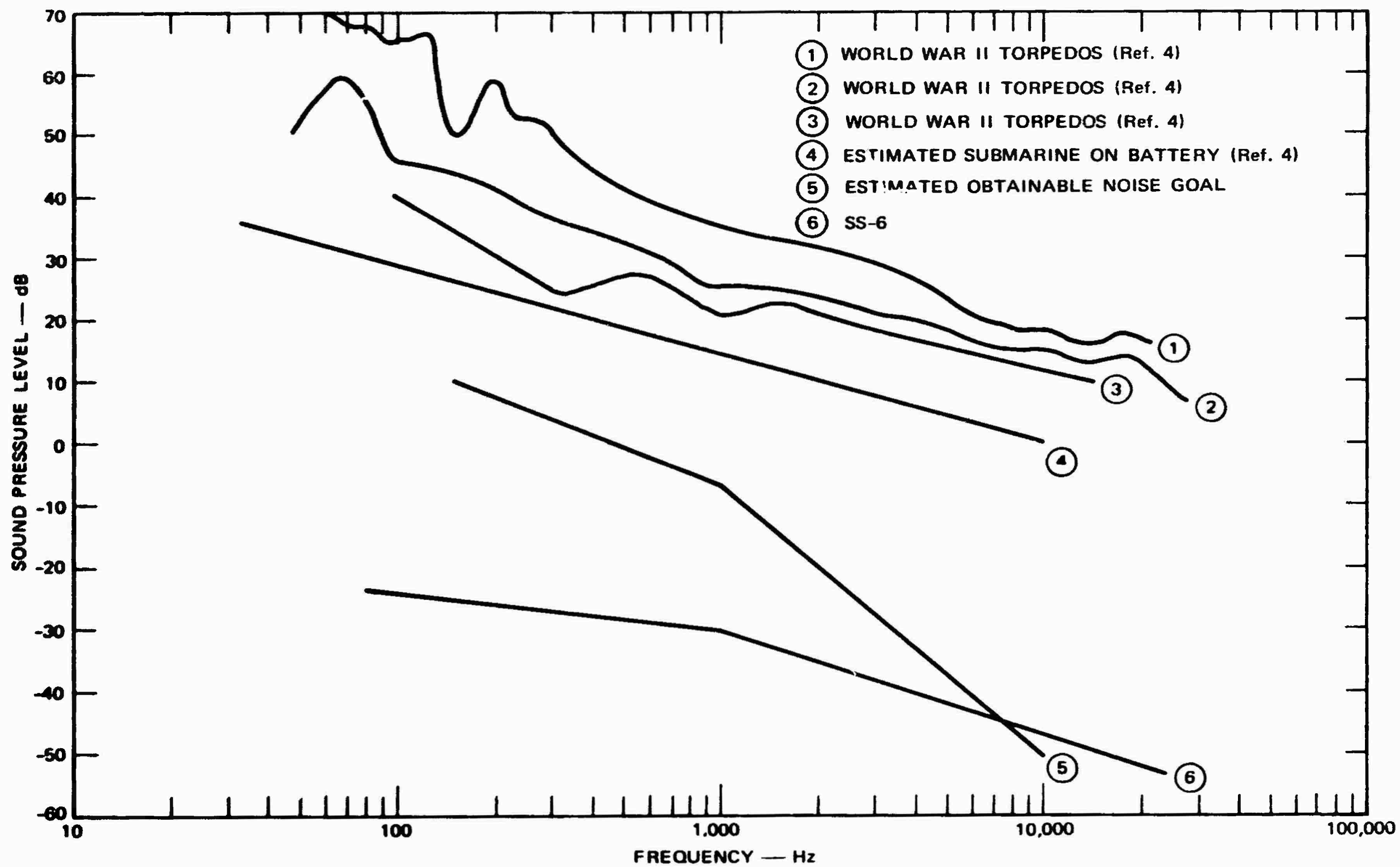

FIGURE V-5 RADIATED NOISE SOURCE LEVELS

It seems reasonable, therefore, to assume that future small submersibles, if not current ones, could be so designed to provide a noise signature no greater than that shown on Fig. V-5 as the obtainable noise goal. If so, this is 15- to 30-dB acoustic advantage for the small covert submersible over a quiet submarine when performing the same covert military mission and when operating against passive surveillance sensors. This noise level difference between the small submersible and the conventional battery submarine is indicated on Fig. V-5 between curves four and five. The passive detection range against the quiet small submersible would probably be less than 10 nmi; and more likely one or two nmi under average conditions.

Active Acoustic Detection

The estimated detection range of a small submersible using an active sonar is determined from the conventional active sonar equation, which is applicable to the detection of a large nuclear submarine, a small submersible, a moored mine, or an underwater swimmer. Under the assumption of noise limiting conditions (no reverberations), the following equation applies:

$$L_E = L_S - 2TL - DI - N + TS$$

where:

L_E = echo level received in dB rel 1 μbar

L_S = source level in dB rel 1 μbar

TL = transmission loss in dB, both spreading loss and absorption loss

DI = isotropic noise reduction in dB due to sonar array and signal procession

N = noise level to 1 μbar

TS = target strength in dB.

This equation and all the variations of each of the parameters is thoroughly discussed in several references (Ref. 4) and will be described here. The primary use of the sonar equation is to indicate the variations in echo level due to the target strength when all other conditions are held constant.

Current sonars, in general, can be divided into mine hunting sonars and submarine detection sonars. The mine hunting sonars operate in frequencies anywhere from 50 kHz to 500 kHz or higher.

None of these sonars was designed to detect small submersibles or underwater swimmers. The mine hunting sonars, however, are probably useful for detecting the underwater swimmer and the older World War II sonars would be better for the larger small submersibles. There is a definite tradeoff between an increase in absorption loss with an increase in operating frequency and a decrease in target strength with decreasing frequency that determines which sonar frequencies are better for different targets, the underwater swimmer or the small submersible. The better sonar for a very small submersible is also probably comparable to a mine hunting sonar; the target strength of small submersibles will be larger, however, than a buoyant mine and more easily detected.

Figure V-6 shows the different target strengths estimated for submarine-like vehicles (a cylindrical tube) with length and diameter as parameters which determine the target strength. The large variations in target strength with both geometry (2rL) and frequency can be noted on this figure. These are the maximum target strengths. In general, the random aspect of the target will reduce these target strengths to lesser values.

With a sonar designed at the lower frequencies, 25 kHz, the small submersible should be detectable at ranges like 4 or 5 nmi.

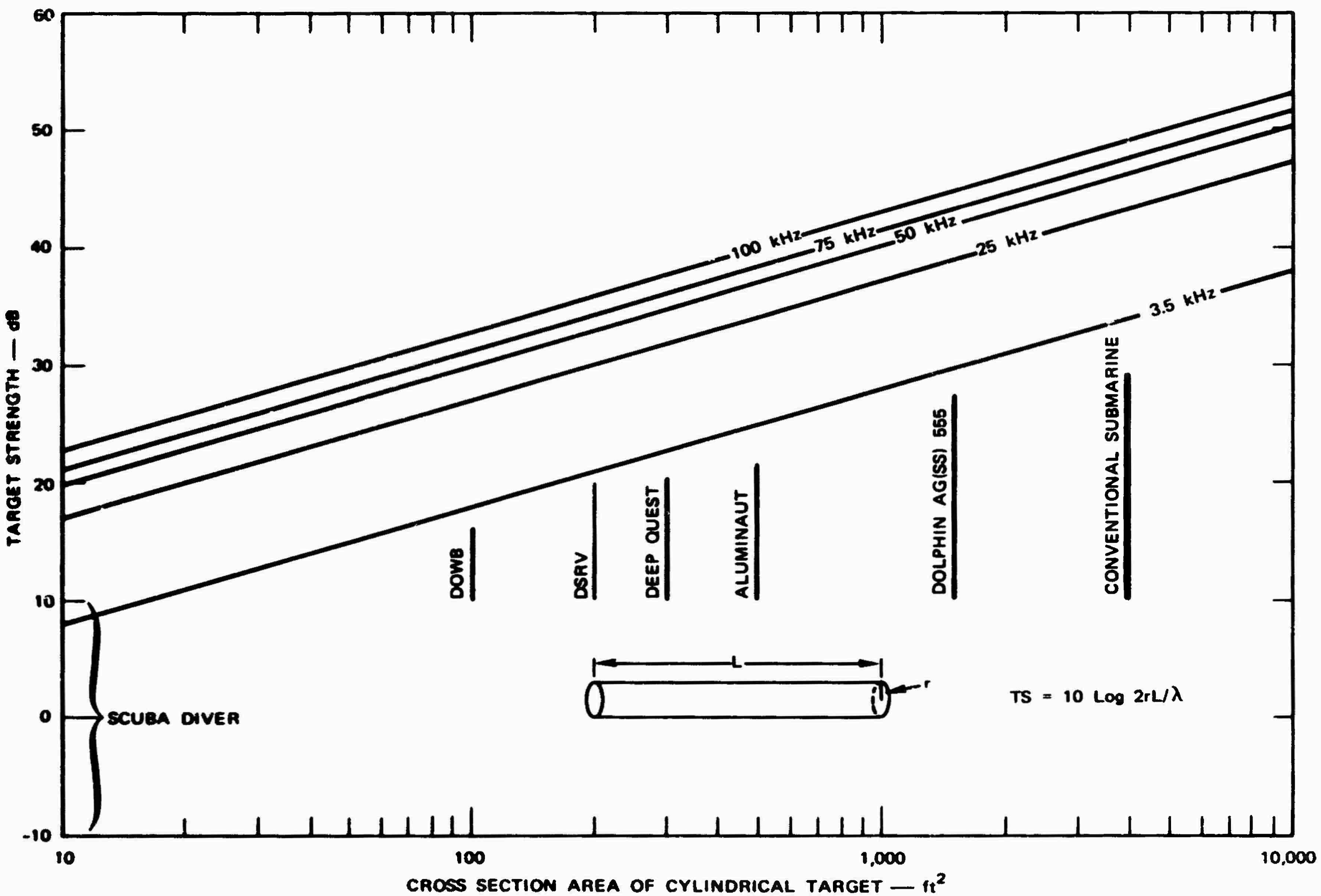

FIGURE V-6 ESTIMATED MAXIMUM (BEAM) TARGET STRENGTHS FOR SUBMERSIBLES AT LONG RANGE

The underwater swimmer target strength is indicated on Fig. V-6 at the bottom. The SCUBA tanks would be applicable to the curves on the chart at 2rL = 1, but the swimmer, with or without a rubber suit providing acoustic absorption and different reflection characteristics, is not.

Experimental target strength measurements of underwater swimmers at relatively key frequencies have an overall range from -40 to -5 dB. Various combinations consisting of different breathing equipment, type of suit, and diver position have been tested--in one case, 12 distinct categories in all. Echo amplitude fluctuation was quite rapid, with angular change, and the directivity pattern for each category had a roughly circular appearance. The average target strength values ranged from -28 to -13 dB. Based on these averages, the open circuit versus closed circuit and wet suit versus dry suit categories showed little change in target strength. The SCUBA equipped skin diver, however, was a consistently poorer target than the others by some 2 to 8 dB. The addition of a cellular rubber wet suit resulted in a 2- to 6-dB increment in both the mean and peak target strength values for the diver.

Rough calculations based on these results indicate that a hostile skin diver, using closed circuit SCUBA and approaching along the bottom, could be detected at a range of 500 yards by a suitably designed and located sonar. With the improvement of sonars designed to detect underwater swimmers, it is reasonable to expect detection with active sonars at ranges to 1,000 yards.

Magnetic Detectability of Small Submersibles and Swimmers

The magnetic detectability of a small submersible or an underwater swimmer is limited. The detectability is dependent upon the measurability of disturbances in the natural magnetic field, which in itself is comprised of large magnetic noise fluctuations.

The two most probable magnetic disturbances would be caused by induction of magnetic fields in the ferromagnetic material associated with either the small submersible or the swimmer, and the magnetic fields generated by wires carrying direct current. The swimmer, when all components of his gear are nonferromagnetic, would create little or no magnetic disturbances for detection. However, any tools or weapons of ferromagnetic materials would offset any design protection measures taken to reduce the swimmer's magnetic detectability. Even with ferromagnetic tools the magnetic detectability would be very limited, probably less than 100 ft.

The estimated magnetic detectability of a small submersible is less than 500 ft. It could easily be no more than 100 ft if the necessary precautions were made to minimize the ferromagnetic materials, degauss the vehicle, and shield all d.c. transmission wiring.

The above detection range estimate is made from Fig. V-7, which relates field intensity at range R from a ferromagnetic material in the earth's magnetic field.[V-5] The general relationships are as follows.

For distance greater than the dimensions of the target, the magnitude of the anomalous magnetic field can be represented by:

$$H = \frac{3P}{R^3} \qquad (1)$$

where

H = Field intensity at distance R

P = Dipole moment

R = Distance from target.

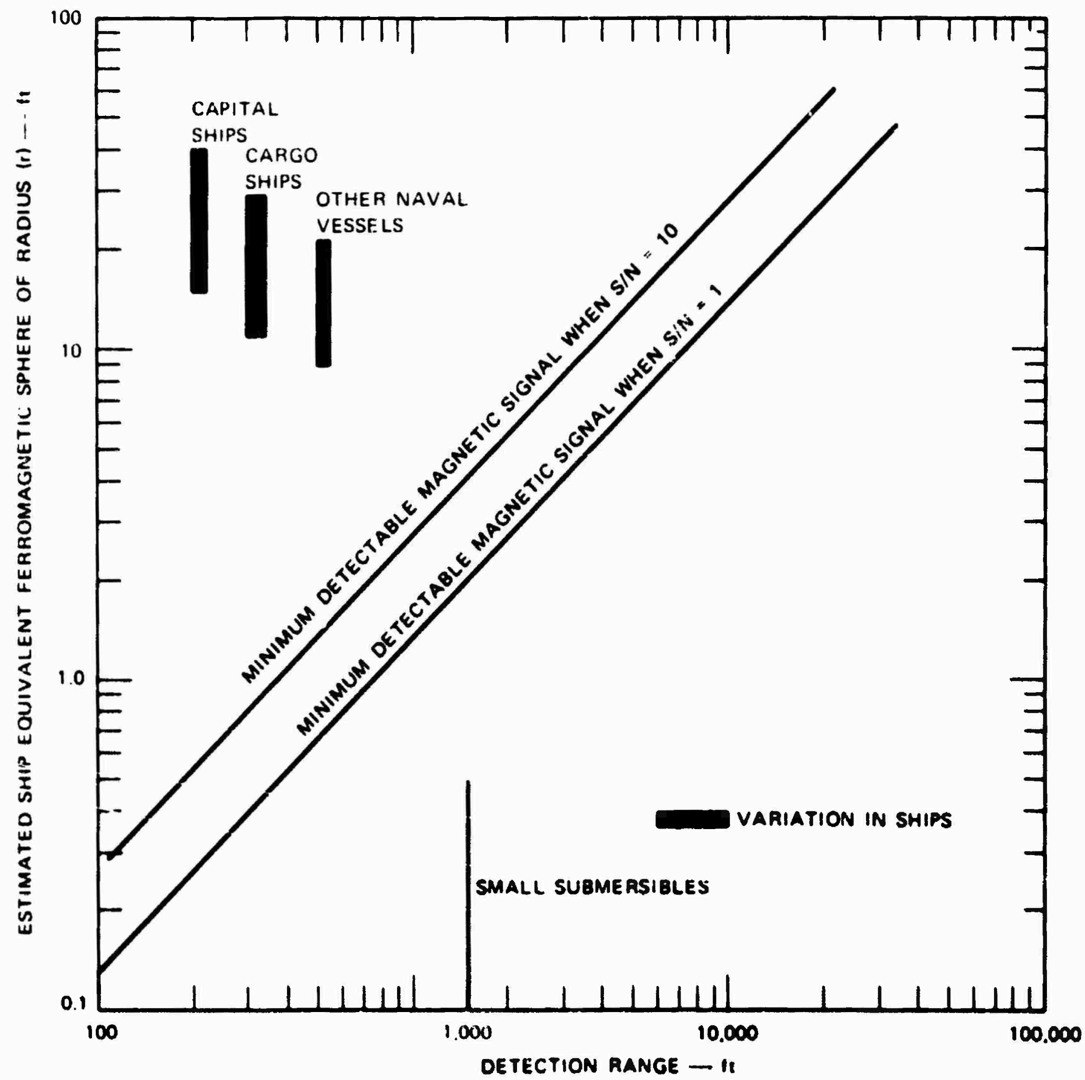

FIGURE V-7 ESTIMATED MAGNETIC DETECTABILITY OF NAVAL VESSELS

A ferromagnetic sphere placed in a magnetic field will possess an induced moment

$$P = \frac{1}{2\pi} VH_o \tag{2}$$

where

V = Volume of the sphere

H_o = Earth magnetic field.

Combining Esq. (1) and (2), and substituting $V = \frac{4}{3}\pi r^3$ where r = radius of sphere,

$$H = 2H_o \left(\frac{r}{R}\right)^3 \tag{3}$$

A magnetostatic fluctuation other than that caused by a target can be classified as noise H_n. Then

$$S/N = \frac{H}{H_n} = \frac{2H_o}{H_n}\left(\frac{r}{R}\right)^3$$

$$R = r\left[\frac{2H_o}{H_n(S/N)}\right]^{1/3} \tag{4}$$

The two values for the limits of detectability as determined by Eq. (4) shown in Fig. 4 are S/N = 1 and S/N = 10.

Magnetic Field from Current Carrying Wires

The detectability from the possible magnetic field generated by d.c. currents through wires aboard the vehicle is not considered to be a problem. I: necessary, the wires can be shielded or wound in such a manner as to reduce the effected magnetic field and related detection range well below those limits indicated on Fig. V-7 for ferromagnetic induction.

E. Functional Requirements for MAN-IN-THE-SEA Systems

The functional requirements for MAN-IN-THE-SEA systems in accomplishing naval undersea missions and operations are identified in Tables V-4 through V-20. The tables identify the generalized tasks associated with a single undersea operation or a specific set of them. The generalized tasks are then related to the performance criteria as shown on the left-hand side of the table. The performance criteria are:

- Depth capability
- Time capability
- Mobility capability
- Load carrying capability
- Maneuvering capability
- Sensory capability
- Cognitive skills
- Hardness
- Covertness.

The comparative analysis of the functional capabilities of MAN-IN-THE-SEA system versus the alternatives based on the foregoing criteria indicates the following:

- MAN-IN-THE-SEA is unique in that:
  - He is compact and agile, which allows him to reach job sites of limited access and in congested structures
  - He possesses manipulative skills unavailable in underwater mechanical manipulators
  - He possesses tactile senses that allow him to accomplish manipulative tasks in extremely turbid waters
  - As a free swimmer, he is relatively covert to visual, acoustic, magnetic, and electrical sensors

- MAN-IN-THE-SEA has capabilities comparable to those of the vehicle oriented systems in operating time and in cognitive skills for on-site assessment of tasks
- MAN-IN-THE-SEA is at a disadvantage when compared with the alternative systems in operating depth capability, mobility capability, load carrying capability, and resistance capability to hazards.

The above comparative analysis results are shown on the right-hand side of Tables V-4 to V-20. An undersea operation is considered a functional role of MAN-IN-THE-SEA systems if it has requirements for the unique capabilities of MAN-IN-THE-SEA systems.

Table V-4

TASK ALLOCATION MATRIX FOR UNDERSEA FUNCTIONAL OPERATIONS: SURVEILLANCE - LANDING BEACH AREA, ENEMY HARBOR, INSHORE USW, USW ALL RANGES AND DEPTHS

Generalized Task Spectrum / Functional Performance Requirements	Class I	Class II			Class III			Class IV																			MAN-IN-THE-SEA Unique Capabilities	MAN-IN-THE-SEA and Alternatives Comparable	Alternatives Unique Capabilities
								Attach						Detach						Apply			Excavate						
	Search Locate	Observe	Survey	Measure	Pickup	Transport	Place	Weld	Drill	Bolt	Rivet	Connect	Clamp	Burn	Pyrotechnic	Drill	Saw	Hammer/chip	Scrape/wipe	Hose	Coat	Paint	Core	Dredge	Trench	Tunnel			
Mobility						■																							■
• Speed																													■
• Range						■																							■
Load Carrying						■																							■
• Object size						■																							■
• Object weight						■																							■
Maneuverability																											■		
• Access limit																											■		
• Degrees freedom																											■		
Manipulation					■		■																					■	
• Minimum skill					■		■																					■	
• Moderate skill																											■		
• Complex skill																											■		
Sensing		■	■																								■	■	■
• Visual		■	■																									■	
• Acoustic		■	■																										■
• Electromagnetic																													■
• Magnetic		■	■																										■
• Electric		■	■																										■
• Tactile																											■		
Cognition		■	■																									■	
• On scene assess.		■	■																									■	
Hardness	Enemy Countermeasures																												■
• Mechanical	• Explosives																												■
• Radiation	• Acoustic noise generators																												■
• Temperature																													■
• Marine life																													■
Covertness	Enemy Countermeasures																										■		
• Visual	• Underwater TV, swimmers																										■		
• Acoustic	• Active and passive sonar																										■		
• Electromagnetic																											■		
• Magnetic	• Magnetic anomaly detectors																										■		
• Electrical	• Electric field detectors																										■		
• Pressure	• Pressure field detectors																										■		

Table V-5

TASK ALLOCATION MATRIX FOR UNDERSEA FUNCTIONAL OPERATIONS: RECONNAISSANCE - BEACH AREA, ENEMY HARBOR, MINING ENVIRONMENT

Generalized Task Spectrum → / Functional Performance Requirements ↓	Class I	Class II			Class III			Class IV																			MAN-IN-THE-SEA Unique Capabilities	MAN-IN-THE-SEA and Alternatives Comparable	Alternatives Unique Capabilities
								Attach						Detach						Apply			Excavate						
	Search Locate	Observe	Survey	Measure	Pickup	Transport	Place	Weld	Drill	Bolt	Rivet	Connect	Clamp	Burn	Pyrotechnic	Drill	Saw	Hammer/chip	Scrape/wipe	Hose	Coat	Paint	Core	Dredge	Trench	Tunnel			
Mobility	■					■																							■
• Speed																													■
• Range	■					■																							■
Load Carrying						■																							■
• Object size						■																							■
• Object weight						■																							■
Maneuverability																											■		
• Access limit																											■		
• Degrees freedom																											■		
Manipulation				■	■		■																					■	
• Minimum skill				■	■		■																					■	
• Moderate skill																											■		
• Complex skill																											■		
Sensing	■		■	■																							■	■	■
• Visual	■		■	■																								■	
• Acoustic	■		■	■																									■
• Electromagnetic																													■
• Magnetic	■		■	■																									■
• Electric	■																												■
• Tactile			■	■																							■		
Cognition	■		■	■	■	■	■																					■	
• On scene assess.	■		■	■	■	■	■																					■	
Hardness	Enemy Countermeasures																												■
• Mechanical	• Explosives																												■
• Radiation	• Acoustic noise generators																												■
• Temperature																													■
• Marine life																													■
Covertness	Enemy Countermeasures																										■		
• Visual	• UW TV, swimmers																										■		
• Acoustic	• Active and passive sonar, acoustic influence mines																										■		
• Electromagnetic																											■		
• Magnetic	• Magnetic anomaly detector, magnetic influence mines																										■		
• Electrical	• Electric field detector																										■		
• Pressure																											■		

Table V-6

TASK ALLOCATION MATRIX FOR UNDERSEA FUNCTIONAL OPERATIONS: MINING - MINE HUNTING AND COUNTERMEASURES

Generalized Task Spectrum / Functional Performance Requirements	Class I	Class II			Class III			Class IV																			MAN-IN-THE-SEA Unique Capabilities	MAN-IN-THE-SEA and Alternatives Comparable	Alternatives Unique Capabilities
								Attach						Detach						Apply			Excavate						
	Search Locate	Observe	Survey	Measure	Pickup	Transport	Place	Weld	Drill	Bolt	Rivet	Connect	Clamp	Burn	Pyrotechnic	Drill	Saw	Hammer/chip	Scrape/wipe	Hose	Coat	Paint	Core	Dredge	Trench	Tunnel			
Mobility	■																												■
• Speed																													■
• Range	■																												■
Load Carrying					■	■	■																						■
• Object size					■	■	■																						■
• Object weight					■	■	■																						■
Maneuverability																											■		
• Access limit																											■		
• Degrees freedom																											■		
Manipulation					■		■																					■	
• Minimum skill					■		■																					■	
• Moderate skill																											■		
• Complex skill																											■		
Sensing	■		■	■																							■	■	■
• Visual	■		■	■																								■	
• Acoustic	■		■	■																									■
• Electromagnetic																													■
• Magnetic	■		■	■																									■
• Electric	■		■	■																									■
• Tactile			■	■																							■		
Cognition	■		■	■																								■	
• On scene assess.	■		■	■																								■	
Hardness	Mine Hazards																												■
• Mechanical	• Explosives																												■
• Radiation																													■
• Temperature																													■
• Marine life																													■
Covertness	Mine Hazards																										■		
• Visual																											■		
• Acoustic	• Acoustic influence mines																										■		
• Electromagnetic																											■		
• Magnetic	• Magnetic influence mines																										■		
• Electrical	• Electric influence mines																										■		
• Pressure	• Pressure influence mines																										■		

Table V-7

TASK ALLOCATION MATRIX FOR UNDERSEA FUNCTIONAL OPERATIONS: MINING - MINE PLANTS

Generalized Task Spectrum → / Functional Performance Requirements ↓	Class I	Class II			Class III			Class IV: Attach						Class IV: Detach						Class IV: Apply			Class IV: Excavate				MAN-IN-THE-SEA Unique Capabilities	MAN-IN-THE-SEA and Alternatives Comparable	Alternatives Unique Capabilities
	Search Locate	Observe	Survey	Measure	Pickup	Transport	Place	Weld	Drill	Bolt	Rivet	Connect	Clamp	Burn	Pyrotechnic	Drill	Saw	Hammer/chip	Scrape/wipe	Hose	Coat	Paint	Core	Dredge	Trench	Tunnel			
Mobility	■					■																							■
• Speed																													■
• Range	■					■																							■
Load Carrying						■																							■
• Object size						■																							■
• Object weight						■																							■
Maneuverability																											■		
• Access limit																											■		
• Degrees freedom																											■		
Manipulation							■																					■	
• Minimum skill							■																					■	
• Moderate skill																											■		
• Complex skill																											■		
Sensing	■																										■	■	■
• Visual	■																											■	
• Acoustic	■																												■
• Electromagnetic																													■
• Magnetic																													■
• Electric																													■
• Tactile																											■		
Cognition	■						■																					■	
• On scene assess.	■						■																					■	
Hardness	Enemy Countermeasures																												■
• Mechanical	• Explosives																												■
• Radiation	• Acoustic noise generators																												■
• Temperature																													■
• Marine life																													■
Covertness	Enemy Countermeasures																										■		
• Visual	• UW TV swimmers																										■		
• Acoustic	• Active and passive sonar																										■		
• Electromagnetic																											■		
• Magnetic	• Magnetic anomaly detector																										■		
• Electrical	• Electric field detector																										■		
• Pressure	• Pressure field detector																										■		

Table V-8

TASK ALLOCATION MATRIX FOR UNDERSEA FUNCTIONAL OPERATIONS: MINING - DISARM MINE

Generalized Task Spectrum / Functional Performance Requirements	Class I	Class II			Class III			Class IV																				MAN-IN-THE-SEA Unique Capabilities	MAN-IN-THE-SEA and Alternatives Comparable	Alternatives Unique Capabilities
								Attach						Detach						Apply			Excavate						
	Search Locate	Observe	Survey	Measure	Pickup	Transport	Place	Weld	Drill	Bolt	Rivet	Connect	Clamp	Burn	Pyrotechnic	Drill	Saw	Hammer/chip	Scrape/wipe	Hose	Coat	Paint	Core	Dredge	Trench	Tunnel			
Mobility																													■
• Speed																													■
• Range																													■
Load Carrying																													■
• Object size																													■
• Object weight																													■
Maneuverability																											■		
• Access limit																											■		
• Degrees freedom																											■		
Manipulation			■	■				■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		■	
• Minimum skill																												■	
• Moderate skill																											■		
• Complex skill			■	■				■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		
Sensing			■	■				■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
• Visual			■	■				■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		■	
• Acoustic																													■
• Electromagnetic																													■
• Magnetic																													■
• Electric																													■
• Tactile			■	■				■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		
Cognition			■	■				■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		■	
• On scene assess.			■	■				■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		■	
Hardness	Mine Hazards																												■
• Mechanical	• Explosives																												■
• Radiation																													■
• Temperature																													■
• Marine life																													■
Covertness	Mine Hazards																										■		
• Visual																											■		
• Acoustic	• Acoustic influence mines																										■		
• Electromagnetic																											■		
• Magnetic	• Magnetic influence mines																										■		
• Electrical	• Electric influence mines																										■		
• Pressure	• Pressure influence mines																										■		

Table V-9

TASK ALLOCATION MATRIX FOR UNDERSEA FUNCTIONAL OPERATIONS: MINING - INTERROGATE MINE FIELD

Generalized Task Spectrum / Functional Performance Requirements	Class I	Class II			Class III			Class IV																			MAN-IN-THE-SEA Unique Capabilities	MAN-IN-THE-SEA and Alternatives Comparable	Alternatives Unique Capabilities
								Attach						Detach						Apply			Excavate						
	Search/Locate	Observe	Survey	Measure	Pickup	Transport	Place	Weld	Drill	Bolt	Rivet	Connect	Clamp	Burn	Pyrotechnic	Drill	Saw	Hammer/chip	Scrape/wipe	Hose	Coat	Paint	Core	Dredge	Trench	Tunnel			
Mobility																													
• Speed																													
• Range																													
Load Carrying																													
• Object size																													
• Object weight																													
Maneuverability																													
• Access limit																													
• Degrees freedom																													
Manipulation																													
• Minimum skill																													
• Moderate skill																													
• Complex skill																													
Sensing																													
• Visual																													
• Acoustic																													
• Electromagnetic																													
• Magnetic																													
• Electric																													
• Tactile																													
Cognition																													
• On scene assess.																													
Hardness	Mine Hazards																												
• Mechanical	• Explosives																												
• Radiation																													
• Temperature																													
• Marine life																													
Covertness	Mine Hazards																												
• Visual																													
• Acoustic	• Acoustic influence mines																												
• Electromagnetic																													
• Magnetic	• Magnetic influence mines																												
• Electrical	• Electric influence mines																												
• Pressure	• Pressure influence mines																												

Table V-10

TASK ALLOCATION MATRIX FOR UNDERSEA FUNCTIONAL OPERATIONS: NAVIGATION SURVEY

Generalized Task Spectrum → / Functional Performance Requirements ↓	Class I	Class II			Class III			Class IV																			MAN-IN-THE-SEA Unique Capabilities	MAN-IN-THE-SEA and Alternatives Comparable	Alternatives Unique Capabilities
								Attach						Detach						Apply			Excavate						
	Search Locate	Observe	Survey	Measure	Pickup	Transport	Place	Weld	Drill	Bolt	Rivet	Connect	Clamp	Burn	Pyrotechnic	Drill	Saw	Hammer/chip	Scrape/wipe	Hose	Coat	Paint	Core	Dredge	Trench	Tunnel			
Mobility	■																												■
• Speed																													■
• Range	■																												■
Load Carrying						■																							■
• Object size						■																							■
• Object weight						■																							■
Maneuverability																											■		
• Access limit																											■		
• Degrees freedom																											■		
Manipulation			■	■	■		■																					■	
• Minimum skill			■	■	■		■																					■	
• Moderate skill																											■		
• Complex skill																											■		
Sensing	■		■	■																							■	■	■
• Visual	■		■	■																								■	
• Acoustic	■		■	■																									■
• Electromagnetic																													■
• Magnetic																													■
• Electric																													■
• Tactile																											■		
Cognition	■		■	■																								■	
• On scene assess.	■		■	■																								■	
Hardness																													■
• Mechanical																													■
• Radiation																													■
• Temperature																													■
• Marine life																													■
Covertness																											■		
• Visual																											■		
• Acoustic																											■		
• Electromagnetic																											■		
• Magnetic																											■		
• Electrical																											■		
• Pressure																											■		

Table V-11

TASK ALLOCATION MATRIX FOR UNDERSEA FUNCTIONAL OPERATIONS: RECOVERY - SMALL OBJECTS

- Torpedoes
- Nuclear Weapons
- Space Hardware

Generalized Task Spectrum → / Functional Performance Requirements ↓	Class I	Class II			Class III			Class IV																			MAN-IN-THE-SEA Unique Capabilities	MAN-IN-THE-SEA and Alternatives Comparable	Alternatives Unique Capabilities
								Attach						Detach						Apply			Excavate						
	Search Locate	Observe	Survey	Measure	Pickup	Transport	Place	Weld	Drill	Bolt	Rivet	Connect	Clamp	Burn	Pyrotechnic	Drill	Saw	Hammer/chip	Scrape/wipe	Move	Coat	Paint	Core	Dredge	Trench	Tunnel			
Mobility																													
• Speed																													
• Range																													
Load Carrying																													
• Object size																													
• Object weight																													
Maneuverability																													
• Access limit																													
• Degrees freedom																													
Manipulation																													
• Minimum skill																													
• Moderate skill																													
• Complex skill																													
Sensing																													
• Visual																													
• Acoustic																													
• Electromagnetic																													
• Magnetic																													
• Electric																													
• Tactile																													
Cognition																													
• On scene assess.																													
Hardness																													
• Mechanical																													
• Radiation	• Nuclear radiation hazards																												
• Temperature																													
• Marine life																													
Covertness																													
• Visual																													
• Acoustic																													
• Electromagnetic																													
• Magnetic																													
• Electrical																													
• Pressure																													

Table V-12

TASK ALLOCATION MATRIX FOR UNDERSEA FUNCTIONAL OPERATIONS: RECOVERY - LARGE OBJECT

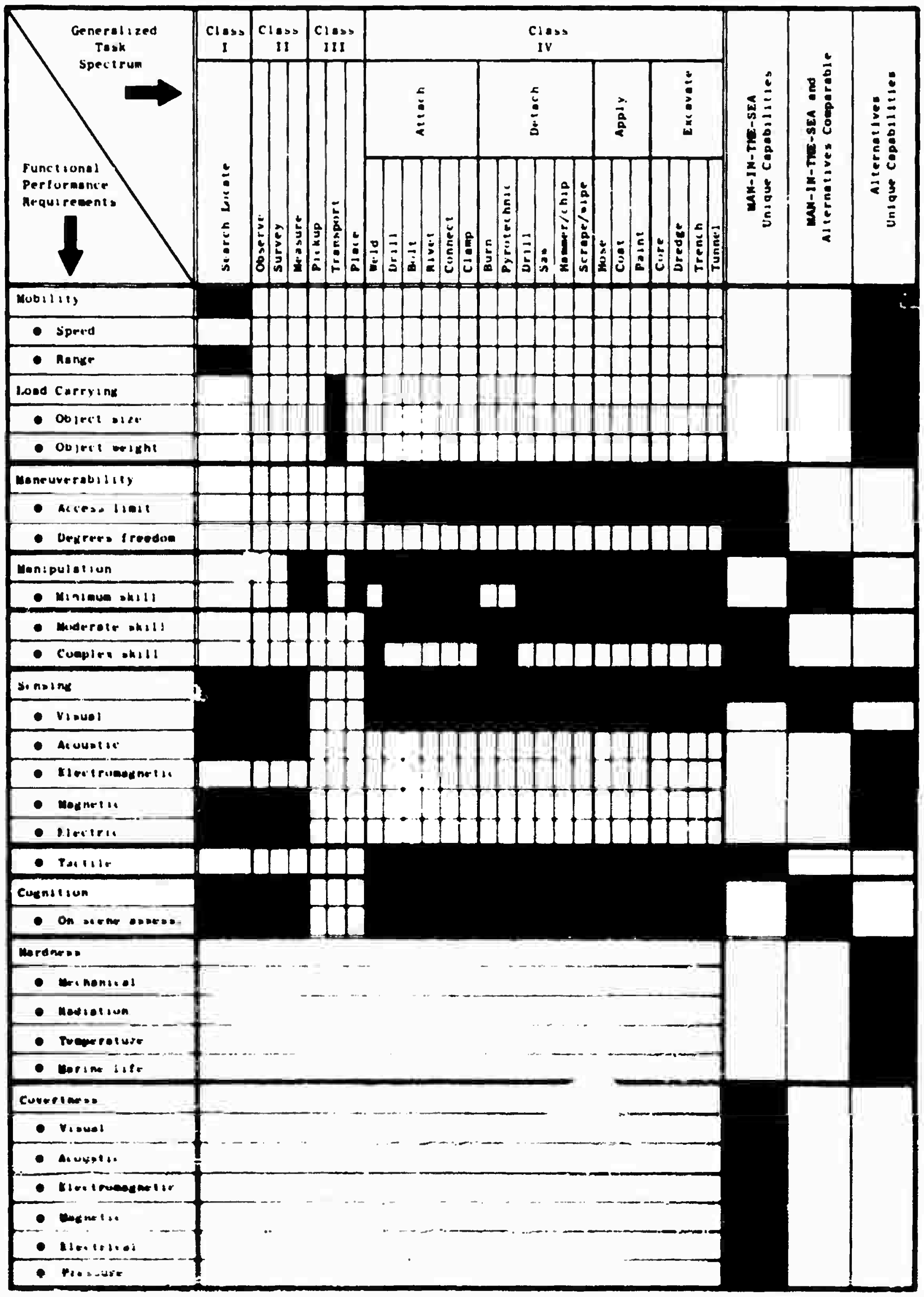

Table V-13

TASK ALLOCATION MATRIX FOR UNDERSEA FUNCTIONAL OPERATIONS:
FACILITY INSTALLATION - SONAR ARRAY (ALIGN & REPAIR),
BOTTOM MOUNTED ULM,
GENERAL CONSTRUCTION

Generalized Task Spectrum / Functional Performance Requirements	Class I	Class II			Class III			Class IV																			MAN-IN-THE-SEA Unique Capabilities	MAN-IN-THE-SEA and Alternatives Comparable	Alternatives Unique Capabilities
								Attach						Detach						Apply			Excavate						
	Search Locate	Observe	Survey	Measure	Pickup	Transport	Place	Weld	Drill	Bolt	Rivet	Connect	Clamp	Burn	Pyrotechnic	Drill	Saw	Hammer/chip	Scraper/wipe	Hose	Coat	Paint	Core	Dredge	Trench	Tunnel			
Mobility																													■
• Speed																													■
• Range																													■
Load Carrying						■																							■
• Object size						■																							■
• Object weight						■																							■
Maneuverability								■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		
• Access limit								■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		
• Degrees freedom																											■		
Manipulation			■	■	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		■	
• Minimum skill			■	■	■		■		■	■	■	■	■			■	■	■	■	■	■	■	■	■	■	■		■	
• Moderate skill								■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		
• Complex skill								■						■	■												■		
Sensing			■	■				■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
• Visual			■	■				■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		■	
• Acoustic																													■
• Electromagnetic																													■
• Magnetic																													■
• Electric																													■
• Tactile								■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		
Cognition			■	■				■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		■	
• On scene assess.			■	■				■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		■	
Hardness																													■
• Mechanical																													■
• Radiation																													■
• Temperature																													■
• Marine life																													■
Covertness																											■		
• Visual																											■		
• Acoustic																											■		
• Electromagnetic																											■		
• Magnetic																											■		
• Electrical																											■		
• Pressure																											■		

Table V-14

TASK ALLOCATION MATRIX FOR UNDERSEA FUNCTIONAL OPERATIONS:
FACILITY INSTALLATIONS - NAVIGATION MARKERS,
CABLE LAYING AND INSPECTION

Generalized Task Spectrum → / Functional Performance Requirements ↓	Class I	Class II			Class III			Class IV																			MAN-IN-THE-SEA Unique Capabilities	MAN-IN-THE-SEA and Alternatives Comparable	Alternatives Unique Capabilities
								Attach						Detach						Apply			Excavate						
	Search Locate	Observe	Survey	Measure	Pickup	Transport	Place	Weld	Drill	Bolt	Rivet	Connect	Clamp	Burn	Pyrotechnic	Drill	Saw	Hammer/chip	Scrape/wipe	Hose	Coat	Paint	Core	Dredge	Trench	Tunnel			
Mobility						■																							■
• Speed																													■
• Range						■																							■
Load Carrying						■																							■
• Object size						■																							■
• Object weight						■																							■
Maneuverability																											■		
• Access limit																											■		
• Degrees freedom																											■		
Manipulation					■		■																	■	■			■	
• Minimum skill					■		■																	■	■			■	
• Moderate skill																											■		
• Complex skill																											■		
Sensing			■	■																				■	■		■	■	■
• Visual			■	■																				■	■			■	
• Acoustic			■	■																									■
• Electromagnetic																													■
• Magnetic																													■
• Electric																													■
• Tactile																											■		
Cognition			■	■	■		■																	■	■			■	
• On scene assess.			■	■	■		■																	■	■			■	
Hardness																													■
• Mechanical																													■
• Radiation																													■
• Temperature																													■
• Marine life																													■
Covertness																											■		
• Visual																											■		
• Acoustic																											■		
• Electromagnetic																											■		
• Magnetic																											■		
• Electrical																											■		
• Pressure																											■		

Table V-15

TASK ALLOCATION MATRIX FOR UNDERSEA FUNCTIONAL OPERATIONS: FACILITY INSTALLATIONS - FOUNDATION AND BOTTOM

Generalized Task Spectrum → / Functional Performance Requirements ↓	Class I	Class II			Class III			Class IV																			MAN-IN-THE-SEA Unique Capabilities	MAN-IN-THE-SEA and Alternatives Comparable	Alternatives Unique Capabilities
								Attach						Detach						Apply			Excavate						
	Search Locate	Observe	Survey	Measure	Pickup	Transport	Place	Weld	Drill	Bolt	Rivet	Connect	Clamp	Burn	Pyrotechnic	Drill	Saw	Hammer/chip	Scrape/wipe	Hose	Coat	Paint	Core	Dredge	Trench	Tunnel			
Mobility																													
• Speed																													
• Range																													
Load Carrying																													
• Object size																													
• Object weight																													
Maneuverability																													
• Access limit																													
• Degrees freedom																													
Manipulation																													
• Minimum skill																													
• Moderate skill																													
• Complex skill																													
Sensing																													
• Visual																													
• Acoustic																													
• Electromagnetic																													
• Magnetic																													
• Electric																													
• Tactile																													
Cognition																													
• On scene assess.																													
Hardness																													
• Mechanical																													
• Radiation																													
• Temperature																													
• Marine life																													
Covertness																													
• Visual																													
• Acoustic																													
• Electromagnetic																													
• Magnetic																													
• Electrical																													
• Pressure																													

Table V-16

TASK ALLOCATION MATRIX FOR UNDERSEA FUNCTIONAL OPERATIONS:
SALVAGE - SHIPS,
AIRCRAFT

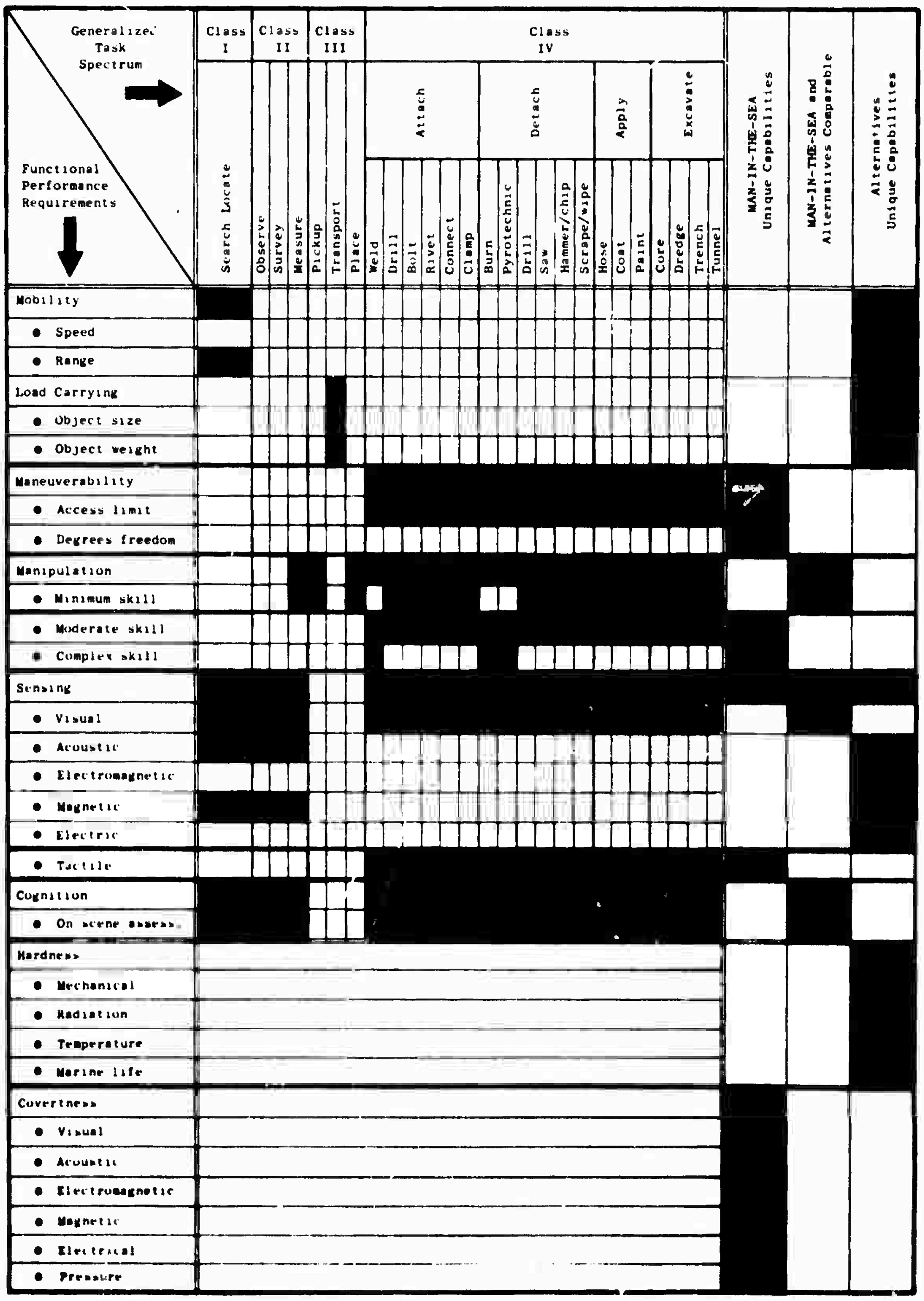

Table V-17

TASK ALLOCATION MATRIX FOR UNDERSEA FUNCTIONAL OPERATIONS:
REPAIRS - IN PORT (WET DOCK)
UNDERWAY

Generalized Task Spectrum / Functional Performance Requirements	Class I	Class II			Class III			Class IV																			MAN-IN-THE-SEA Unique Capabilities	MAN-IN-THE-SEA and Alternatives Comparable	Alternatives Unique Capabilities
								Attach						Detach						Apply			Excavate						
	Search Locate	Observe	Survey	Measure	Pickup	Transport	Place	Weld	Drill	Bolt	Rivet	Connect	Clamp	Burn	Pyrotechnic	Drill	Saw	Hammer/chip	Scrape/wipe	Hose	Coat	Paint	Core	Dredge	Trench	Tunnel			
Mobility																													■
• Speed																													■
• Range																													■
Load Carrying																													■
• Object size																													■
• Object weight																													■
Maneuverability								■	■	■	■	■	■	■	■	■	■	■	■	■	■	■					■		
• Access limit								■	■	■	■	■	■	■	■	■	■	■	■	■	■	■					■		
• Degrees freedom																											■		
Manipulation								■	■	■	■	■	■	■	■	■	■	■	■	■	■	■						■	
• Minimum skill									■	■	■	■	■			■	■	■	■	■	■	■						■	
• Moderate skill								■	■	■	■	■	■	■	■	■	■	■	■	■	■	■					■		
• Complex skill								■						■	■												■		
Sensing								■	■	■	■	■	■	■	■	■	■	■	■	■	■	■					■	■	■
• Visual								■	■	■	■	■	■	■	■	■	■	■	■	■	■	■						■	
• Acoustic																													■
• Electromagnetic																													■
• Magnetic																													■
• Electric																													■
• Tactile								■	■	■	■	■	■	■	■	■	■	■	■	■	■	■					■		
Cognition								■	■	■	■	■	■	■	■	■	■	■	■	■	■	■						■	
• On scene assess.								■	■	■	■	■	■	■	■	■	■	■	■	■	■	■						■	
Hardness																													■
• Mechanical																													■
• Radiation																													■
• Temperature																													■
• Marine life																													■
Covertness																											■		
• Visual																											■		
• Acoustic																											■		
• Electromagnetic																											■		
• Magnetic																											■		
• Electrical																											■		
• Pressure																											■		

Table V-18
TASK ALLOCATION MATRIX FOR UNDERSEA FUNCTIONAL OPERATIONS:
SUPPORT - OCEANOGRAPHIC DATA

Generalized Task Spectrum → / Functional Performance Requirements ↓	Class I	Class II			Class III			Class IV																			MAN-IN-THE-SEA Unique Capabilities	MAN-IN-THE-SEA and Alternatives Comparable	Alternatives Unique Capabilities
								Attach						Detach						Apply			Excavate						
	Search Locate	Observe	Survey	Measure	Pickup	Transport	Place	Weld	Drill	Bolt	Rivet	Connect	Clamp	Burn	Pyrotechnic	Drill	Saw	Hammer/chip	Scrape/wipe	Hose	Coat	Paint	Core	Dredge	Trench	Tunnel			
Mobility																													
• Speed																													
• Range																													
Load Carrying																													
• Object size																													
• Object weight																													
Maneuverability																													
• Access limit																													
• Degrees freedom																													
Manipulation																													
• Minimum skill																													
• Moderate skill																													
• Complex skill																													
Sensing																													
• Visual																													
• Acoustic																													
• Electromagnetic																													
• Magnetic																													
• Electric																													
• Tactile																													
Cognition																													
• On scene assess.																													
Hardness																													
• Mechanical																													
• Radiation																													
• Temperature																													
• Marine life																													
Covertness																													
• Visual																													
• Acoustic																													
• Electromagnetic																													
• Magnetic																													
• Electrical																													
• Pressure																													

Table V-19

TASK ALLOCATION MATRIX FOR UNDERSEA FUNCTIONAL OPERATIONS: SUPPORT - SUBMARINE RESCUE PERSONNEL

Generalized Task Spectrum → / Functional Performance Requirements ↓	Class I	Class II			Class III			Class IV																				MAN-IN-THE-SEA Unique Capabilities	MAN-IN-THE-SEA and Alternatives Comparable	Alternatives Unique Capabilities
								Attach						Detach						Apply			Excavate						
	Search Locate	Observe	Survey	Measure	Pickup	Transport	Place	Weld	Drill	Bolt	Rivet	Connect	Clamp	Burn	Pyrotechnic	Drill	Saw	Hammer/chip	Scrape/wipe	Hose	Coat	Paint	Core	Dredge	Trench	Tunnel			
Mobility	■																												■
• Speed	■																												■
• Range	■																												■
Load Carrying						■																							■
• Object size						■																							■
• Object weight						■																							■
Maneuverability								■	■	■	■	■	■	■	■	■	■	■	■								■		
• Access limit								■	■	■	■	■	■	■	■	■	■	■	■								■		
• Degrees freedom																											■		
Manipulation					■		■	■	■	■	■	■	■	■	■	■	■	■	■									■	
• Minimum skill					■		■		■	■	■	■	■			■	■	■	■									■	
• Moderate skill							■	■	■	■	■	■	■	■	■	■	■	■	■								■		
• Complex skill								■						■	■												■		
Sensing	■	■	■																								■	■	■
• Visual	■	■	■																									■	
• Acoustic	■	■	■																										■
• Electromagnetic	■	■	■																										■
• Magnetic	■	■	■																										■
• Electric	■	■	■																										■
• Tactile																											■		
Cognition	■	■	■				■	■	■	■	■	■	■	■	■	■	■	■	■									■	
• On scene assess.	■	■	■				■	■	■	■	■	■	■	■	■	■	■	■	■									■	
Hardness																													■
• Mechanical																													■
• Radiation																													■
• Temperature																													■
• Marine life																													■
Covertness																											■		
• Visual																											■		
• Acoustic																											■		
• Electromagnetic																											■		
• Magnetic																											■		
• Electrical																											■		
• Pressure																											■		

Table V-20

TASK ALLOCATION MATRIX FOR UNDERSEA FUNCTIONAL OPERATIONS: SUPPORT - UNDERWATER LOGISTICS

Generalized Task Spectrum → / Functional Performance Requirements ↓	Class I	Class II			Class III			Class IV																			MAN-IN-THE-SEA Unique Capabilities	MAN-IN-THE-SEA and Alternatives Comparable	Alternatives Unique Capabilities
								Attach						Detach						Apply			Excavate						
	Search Locate	Observe	Survey	Measure	Pickup	Transport	Place	Weld	Drill	Bolt	Rivet	Connect	Clamp	Burn	Pyrotechnic	Drill	Saw	Hammer/chip	Scrape/wipe	Hose	Coat	Paint	Core	Dredge	Trench	Tunnel			
Mobility						■																							■
• Speed						■																							■
• Range						■																							■
Load Carrying						■																							■
• Object size						■																							■
• Object weight						■																							■
Maneuverability																											■		
• Access limit																											■		
• Degrees freedom																											■		
Manipulation					■		■					■	■				■	■	■	■								■	
• Minimum skill					■		■					■	■				■	■	■	■								■	
• Moderate skill																											■		
• Complex skill																											■		
Sensing	■																										■	■	■
• Visual	■																											■	
• Acoustic	■																												■
• Electromagnetic																													■
• Magnetic																													■
• Electric																													■
• Tactile																											■		
Cognition		■										■	■					■	■	■	■							■	
• On scene assess.		■										■	■					■	■	■	■							■	
Hardness																													■
• Mechanical																													■
• Radiation																													■
• Temperature																													■
• Marine life																													■
Covertness																											■		
• Visual																											■		
• Acoustic																											■		
• Electromagnetic																											■		
• Magnetic																											■		
• Electrical																											■		
• Pressure																											■		

F. Functional Role of MAN-IN-THE-SEA Systems

The functional role of MAN-IN-THE-SEA systems in accomplishing naval underseas missions is summarized in Table V-21. The table has three major points. First is an indication of MAN-IN-THE-SEA missions and operations if system survivability during a mission emphsizes the use of covert operation. Second, the case is considered where system survivability is achieved through the use of hardened systems. Finally, the case of hardened systems is extended to include the possibility of designing undersea facilities to minimize constraints imposed by the limitations of mechanical manipulator equipped vehicle systems.

Table V-21

SUMMARY OF THE FUNCTIONAL ROLE OF MAN-IN-THE-SEA SYSTEMS

Functional Operations \ Mission Conditions	Condition I Mission Emphasis on the Use of Covert Operations	Condition II Mission Emphasis on the Use of Hardened Systems	Condition II' And the Advanced Design of Underseas Structures
Surveillance	■		
● Landing beach area	■		
● Enemy harbor	■		
● U.S. harbor protection			
● Inshore USW	■		
● USW all ranges and depths			
Reconnaissance	■		
● Beach area	■		
● Enemy harbor	■		
● Mining environment	■		
Mining	■	■	■
● Mine hunting and countermeasures	■		
● Mine plants			
● Disarm mine	■	■	■
● Interrogate mine fields	■		
Navigation Surveys			
Recovery	■	■	■
● Small object	■		
Torpedoes	■		
Nuclear weapon	■		
Space hardware	■		
● Large object	■	■	■
Facility Installations	■	■	
● Sonar array (align and repair)	■	■	
● Bottom mounted ULM	■	■	
● Navigation markers			
● Cable laying and inspection	■	■	
● General construction			
● Foundation and bottom	■	■	■
Salvage	■	■	■
● Ship	■	■	■
● Aircraft	■	■	■
Repairs	■	■	■
● In port (wet dock)	■	■	■
● Underway	■	■	■
Support	■	■	■
● Oceanographic data			
● Sub rescue personnel	■	■	
● Underwater logistics	■	■	■
● Habitat Development	■	■	

■ MAN-IN-THE-SEA functional application area

VI COST COMPARISON

A. Comparison Method

The approach used to make the cost comparison of MAN-IN-THE-SEA systems versus alternative systems is summarized in Fig. VI-1.* The spectrum of MAN-IN-THE-SEA systems options and alternative systems options defined in Section IV are compared for a selected set of five underseas operations. These five operations are:

1. Small object recovery
2. Aircraft salvage
3. Ship salvage
4. Simple undersea construction
5. Undersea facilities construction.

Each operation is addressed separately in the following sections of this report. The procedure is to first select the specific MAN-IN-THE-SEA and alternative systems options that are to be compared. Next, a task-time distribution relationship is generated for both MAN-IN-THE-SEA and alternative systems options. This task-time distribution is generated from two inputs. The first is the detailed task analysis presented in Appendix A to this report. The second is a judgment of the functional capabilities of MAN-IN-THE-SEA and alternative systems that have a tendency to cause a relative time difference in accomplishing a specific task. The comparison of the functional capabilities of MAN-IN-THE-SEA and alternatives conducted in Section V of this report provide the basis for the judgment. A clear example of functional capabilities that contribute

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* See Appendix D for a summary of cost data used in cost comparisons.

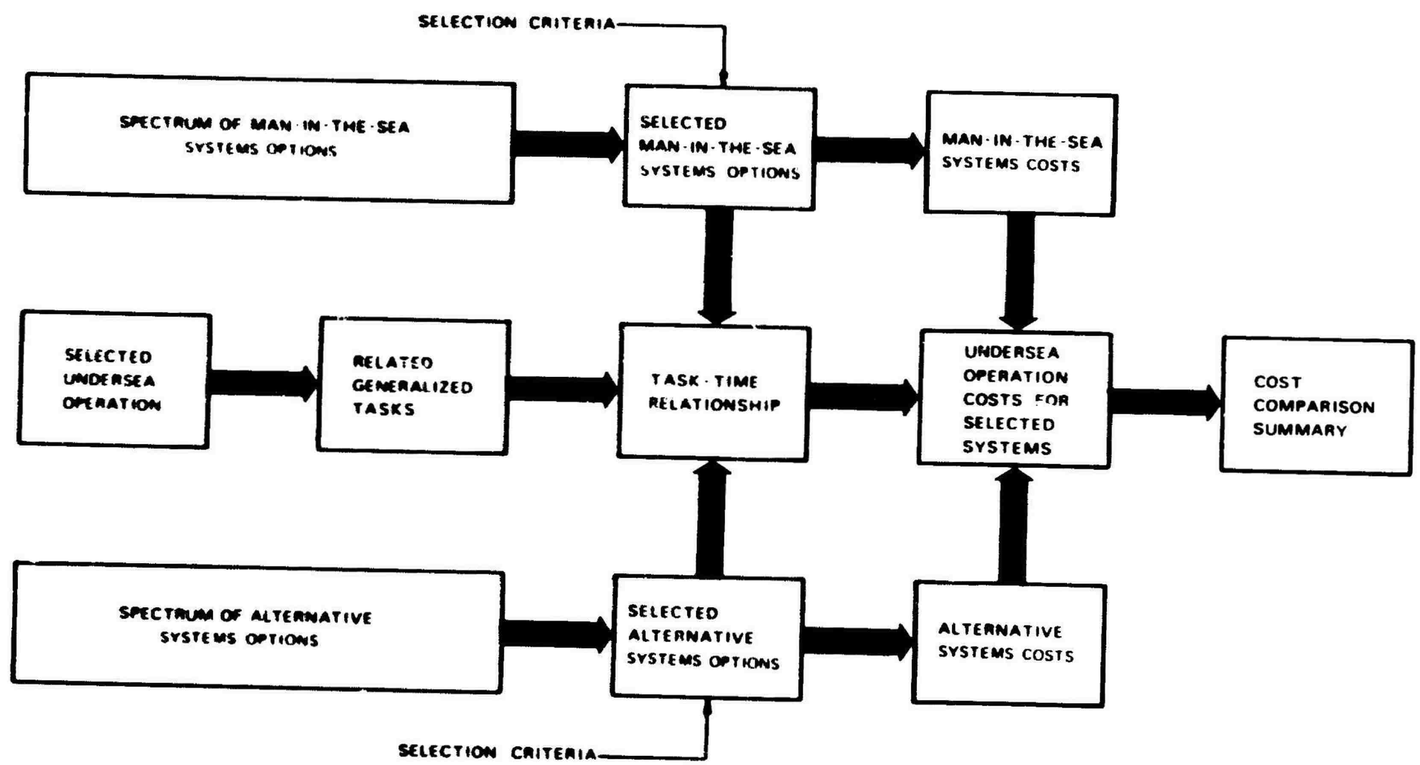

FIGURE VI-1 SUMMARY OF APPROACH USED FOR COST COMPARISON OF MAN-IN-THE-SEA AND ALTERNATIVES toward time difference is the manipulative capability of man versus mechanical manipulators.

The undersea operation costs are compared in two forms. The first is the comparison of the systems investment costs and, second, the comparison of operating costs for the completion of a specific operation, e.g., aircraft salvage or ship salvage. It has been assumed that research and development costs for MAN-IN-THE-SEA systems and the alternative systems are comparable. Furthermore, it is assumed that the operating lives of the systems are equal. The two remaining parameters that would contribute to differentials in operation cost, then, are the systems procurement costs and the daily operating costs. In keeping with the subjective nature of the overall study, the cost comparison is made on an order of magnitude basis. Upper and lower bound cost figures are used so that a range of possible costs are compared. The investment and operating costs include only those costs directly related to the work systems. Work systems as defined here include only those elements directly related with elements that perform undersea tasks, namely, the divers and their support vessel and equipment and the undersea vehicles and their support vessel. The costs of the elements that are being worked on, i.e., the underwater structure or the pontoons and lift devices required for salvage operations, are excluded.

B. Cost Comparison For Small Object Recovery Operation

1. MAN-IN-THE-SEA Systems Options

MAN-IN-THE-SEA work systems options selected for small object recovery operations are shown in Table VI-1. The direct surface supported systems are separated into three depth regimes that reflect the differences in requirements for decompression facilities for air and mixed gas operations. The personnel transfer capsule (PTC) augmented surface supported system, together with the personnel transfer vehicle (PTV) augmented system, are considered for both the surface-to-subsurface cycling operation and the surface-to-habitat operation. The latter is included strictly for comparative purposes since operationally one would not consider using a habitat for short duration operations such as small object recovery.

A four-man work team was postulated for the operation. This constitutes a minimum size work team since it represents the operational allocation of two working personnel with two surface backup personnel.

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Table VI-1

MAN-IN-THE-SEA SYSTEMS OPTIONS AND COSTS

MAN-IN-THE-SEA Systems Options			Operational Life Support Components								Personnel Life Support Components		Support Vessel	
Category	Applicable Depth Regime	Breathing Mixture	Decompression Facilities		Personnel Transfer Capsule (PTC)		Personnel Transfer Vehicle (PTV)		Habitat		P $/man	O $/man/day	P	O
			P	O	P	O	P	O	P	O				
Direct Surface Supported System	0-30 ft	Air									$1,000 / 500	$<10	3 tons** $20,000 / 10,000	$30 / 20
	30-150 ft	Air	$3,000* / 2,000	$<10							$1,000 / 500	$<10	3 tons $20,000 / 10,000	$30 / 20
	150-300 ft	Mixed $He-N_2-O_2$	$2,000,000 / 1,000,000	$200 / 100							$5,000 / 3,000	$30 / 20	50 tons $150,000 / 80,000	$300 / 150
Augmented Surface Supported System (PTC)	300 ft	Mixed $He-N_2-O_2$	↓	↓	$500,000 / 300,000	$200 / 100					↓	↓	500 tons $2,000,000 / 1,000,000	$2,000 / 1,000
	300 ft	Mixed $He-N_2-O_2$	↓	↓	↓	↓			$1,000,000 / 500,000	$500 / 250	↓	↓	1,000 tons $4,000,000 / 2,000,000	$4,000 / 2,000
Augmented Surface Supported System (PTV)	300 ft	Mixed $He-N_2-O_2$	↓	↓			$1,000,000 / 500,000	$1,500 / 1,000			↓	↓	500 tons $2,000,000 / 1,000,000	$2,000 / 1,000
	300 ft	Mixed $He-N_2-O_2$	↓	↓			↓	↓	$1,000,000 / 500,000	$500 / 250	↓	↓	1,000 tons $4,000,000 / 2,000,000	$4,000 / 2,000

P -- Procurement cost.

O -- Operating cost ($/day).

* -- High cost estimate / Low cost estimate

** -- Surface support vessel displacement.

2. Alternative Systems Options

Work system alternatives to MAN-IN-THE-SEA systems selected for small object recovery operations are shown in Table VI-2. The systems options, all supported by surface platforms, are the following:

- Manned free swimming vehicles such as the ALVIN, AUTEC or BEAVER MARK IV
- Manned tethered vehicles such as the ARTICULATED DIVING DRESS and the GUPPY
- Unmanned tethered vehicles such as the remote cable controlled CURV.

Table VI-2

ALTERNATIVE SYSTEMS OPTIONS AND COSTS

System Options		Vehicle Cost		Support Vessel Cost	
Category	Examples	Procurement	Operating ($/day)	Procurement	Operating ($/day)
Manned free vehicles	ALVIN AUTEC BEAVER	$1,000,000* 500,000	$1,500 1,000	500 tons** $2,000,000 1,000,000	$2,000 1,000
Manned tethered vehicle	ARTICULATE DIVING DRESS (300 ft max)	$ 20,000 10,000	$ 200 100	50 tons $ 150,000 80,000	$ 300 150
	GUPPY	$ 200,000 150,000	$1,000 500	500 tons $2,000,000 1,000,000	$2,000 1,000
Unmanned tethered vehicle	CURV	$1,000,000 500,000	$ 500 250	500 tons $2,000,000 1,000,000	$2,000 1,000

* High cost estimate / Low cost estimate

** Surface support vessel displacement

3. Task-Time Distributions

The task-time distribution for small object recovery operation is shown in Tables VI-3 through VI-6. The four basic tasks outlined for small object recovery operations are: (1) search and location of the object, (2) survey of object to determine recovery method, (3) connection of object recovery or lifting device, and (4) observation of final recovery task.

The task-time distribution's dependency upon the specific work system being used is indicated in the tables. The total operation time and the fraction of total operation time required to accomplish specific task vary for work system type. For example:

- Total operation time for tethered MAN-IN-THE-SEA and tethered manned and unmanned vehicles is much greater than for the free swimming MAN-IN-THE-SEA and manned vehicle systems. This is due primarily to the mobility of the free swimming systems.
- Survey time for all systems is equivalent.
- Manipulative time, that required for connecting recovery device on the object, is 100 times greater for the alternative systems as compared with the MAN-IN-THE-SEA systems.

Table VI-3

TASK-TIME DISTRIBUTION FOR SMALL OBJECT RECOVERY OPERATION:
DIRECT SURFACE SUPPORTED AND PTC AUGMENTED SURFACE SUPPORTED MAN-IN-THE-SEA SYSTEMS

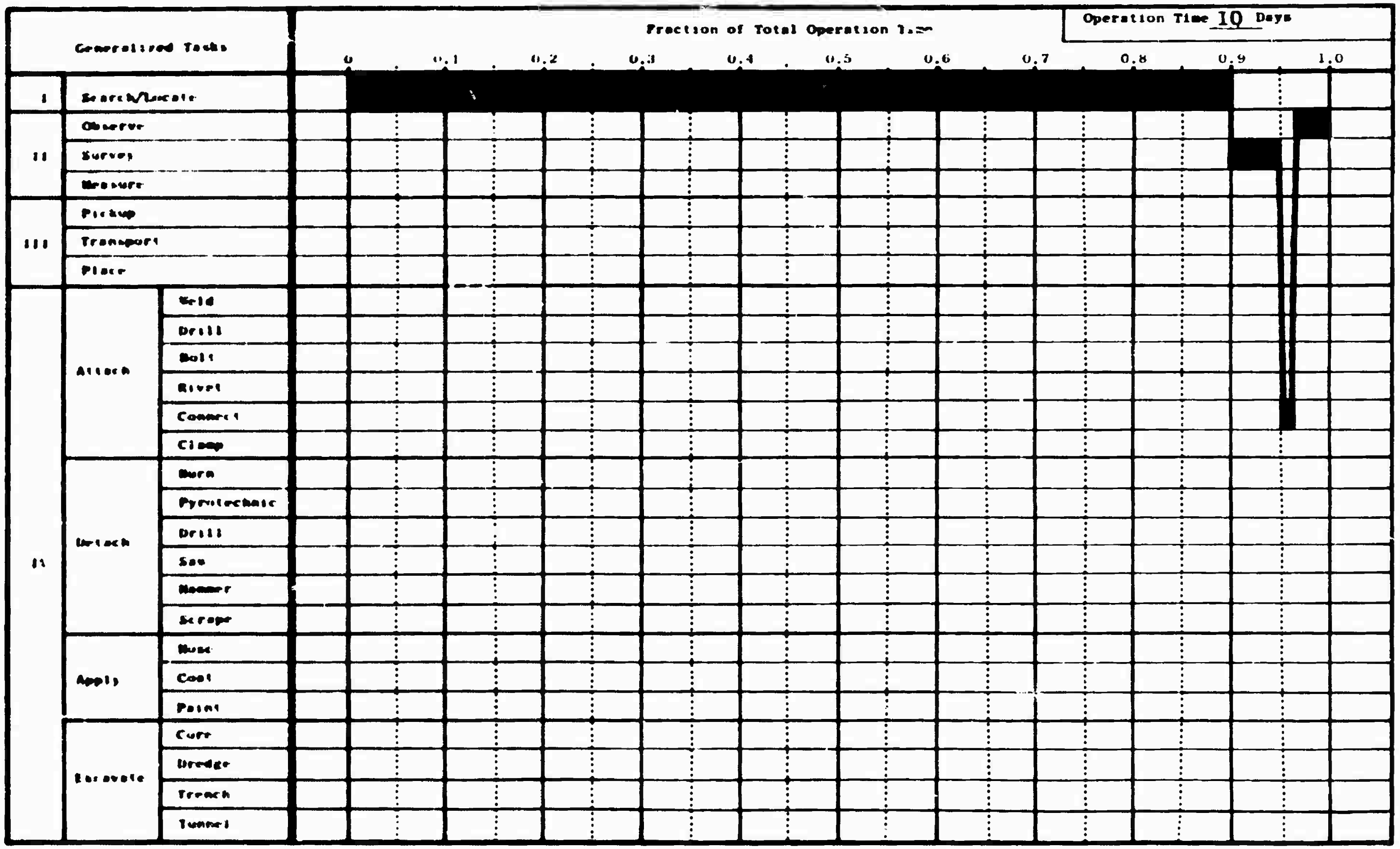


Table VI-4

TASK-TIME DISTRIBUTION FOR SMALL OBJECT RECOVERY OPERATION:
PTV AUGMENTED SURFACE SUPPORTED MAN-IN-THE-SEA SYSTEMS

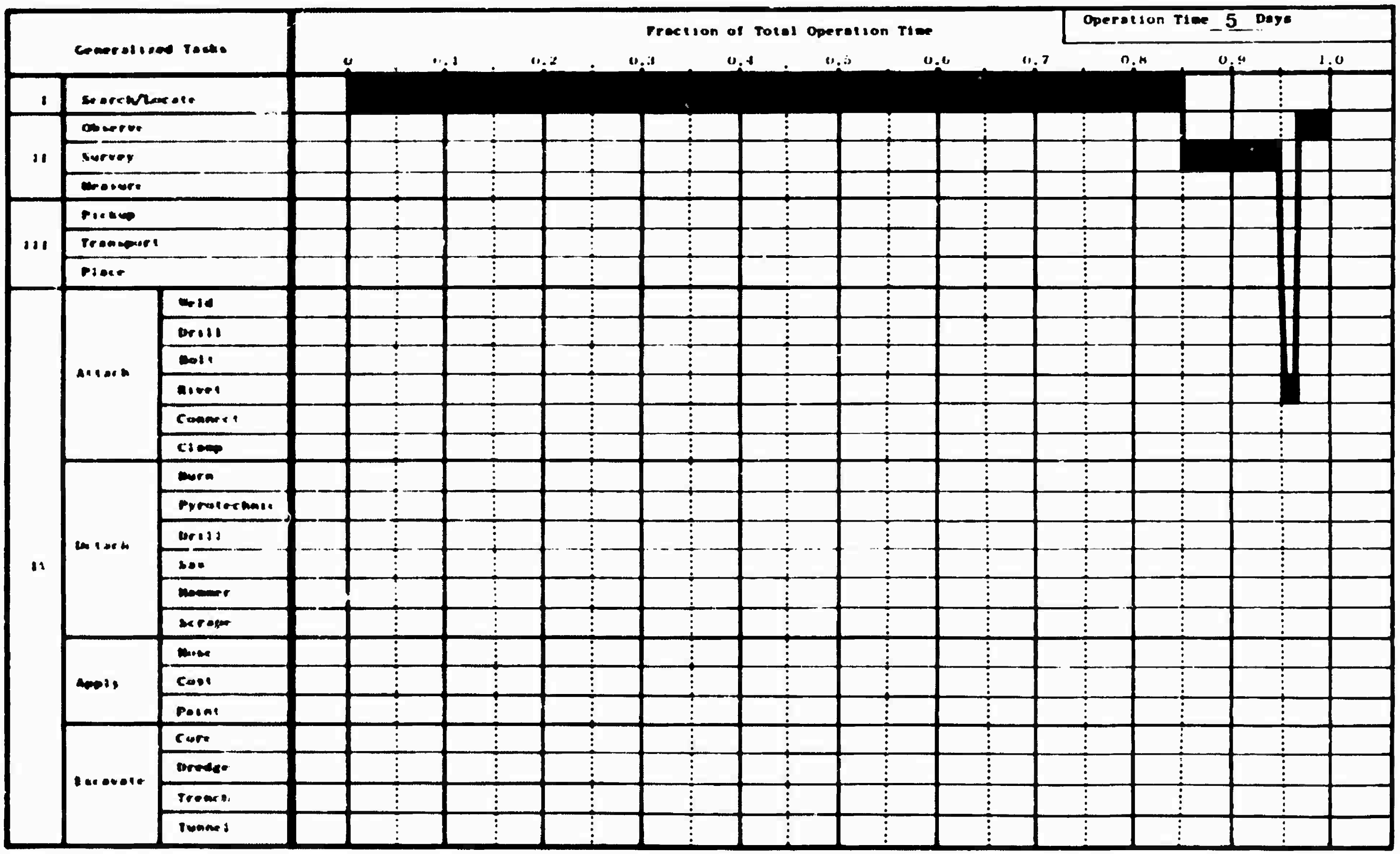


Table VI-5

TASK-TIME DISTRIBUTION FOR SMALL OBJECT RECOVERY OPERATION: SURFACE SUPPORTED MANNED FREE SWIMMING VEHICLES

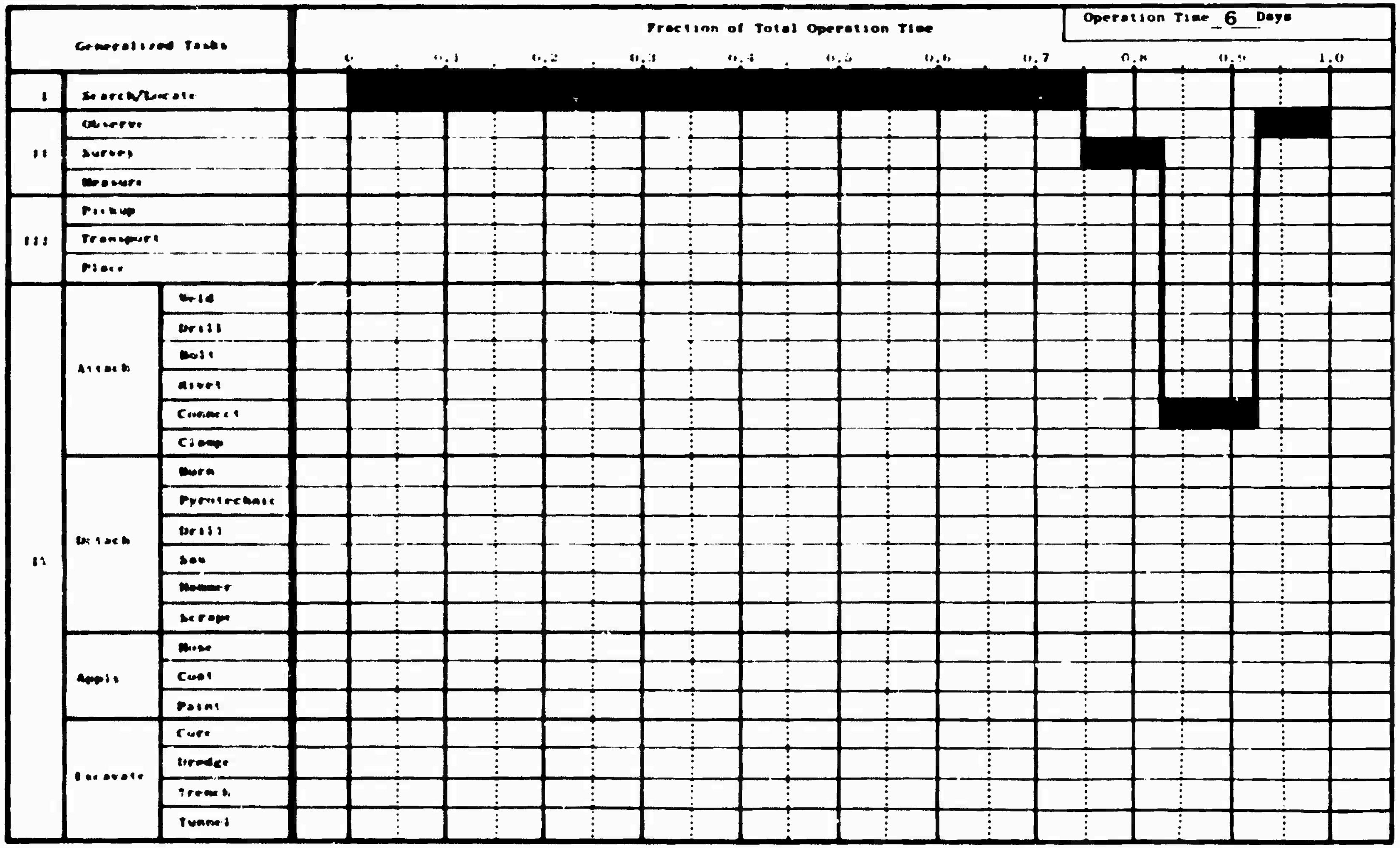
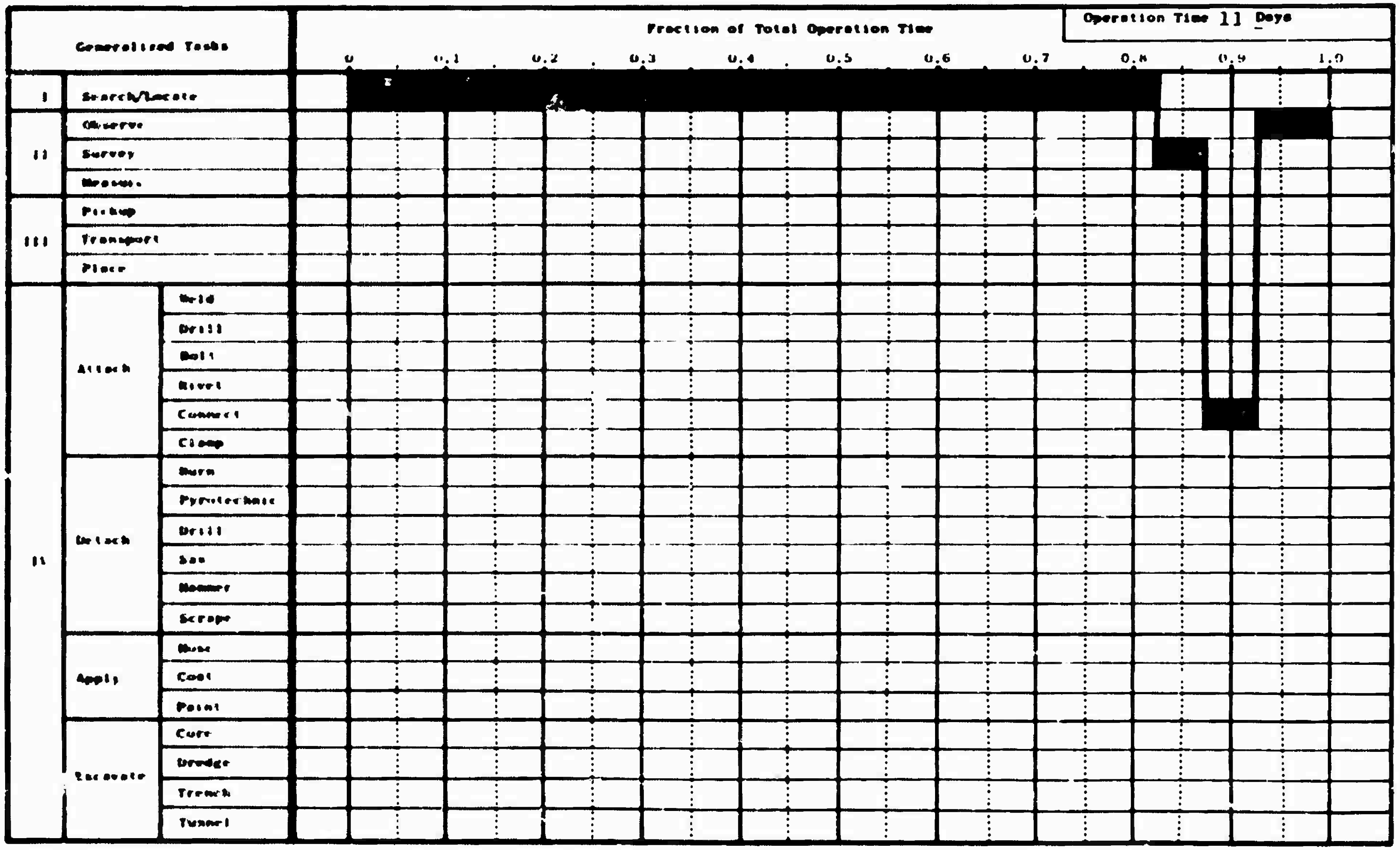


Table VI-6

TASK-TIME DISTRIBUTION FOR SMALL OBJECT RECOVERY OPERATION: SURFACE SUPPORTED MANNED AND UNMANNED TETHERED VEHICLES



4. Small Object Recovery Operation Cost Comparison Summary

The comparison of the work systems investment costs is shown in Figs. VI-2 and VI-3. Figure VI-2 compares the investment costs without the cost of the surface support ship. Figure VI-3 compares the investment costs where the surface support ship cost is included.

The comparison of the work systems operating costs is shown in Figs. VI-4 and VI-5, where operating costs are those for the entire projected duration of the small object recovery operation. Figure VI-4 compares the operating costs without the operating costs of the surface support ship. Figure VI-5 compares the operating costs where the surface support ship cost is included.

In both investment and operating cost comparisons the costs are represented in the form of high and low cost estimates. Thus, for each system and applicable depth range, the comparison curves are presented as a cost band. Where the costs of MAN-IN-THE-SEA systems are highly depth dependent, alternative systems costs are relatively independent of depth. The latter is because vehicles are designed for a specific maximum operating depth with an associated system cost. This cost will remain fixed for the entire operating depth regime of the system. A summary of comparison results follows:

- The dominant investment and operating costs of postulated systems for small object recovery operations are for the surface support vessel.
- For operating depths up to 150 ft MAN-IN-THE-SEA systems have definite investment and operating cost advantages over alternative work systems. This advantage holds for the case where support vessel costs were not included and the case where support vessel costs were included.

- For depths up to 300 ft the ARTICULATED DIVING DRESS has the advantage in system investment costs. However, the operating costs of MAN-IN-THE-SEA systems are comparable to those of the diving dress.
- For depths beyond 300 ft MAN-IN-THE-SEA systems have investment and operating costs comparable to the alternative systems. In fact, the alternatives have a slight investment cost advantage if support vessel costs are not included.

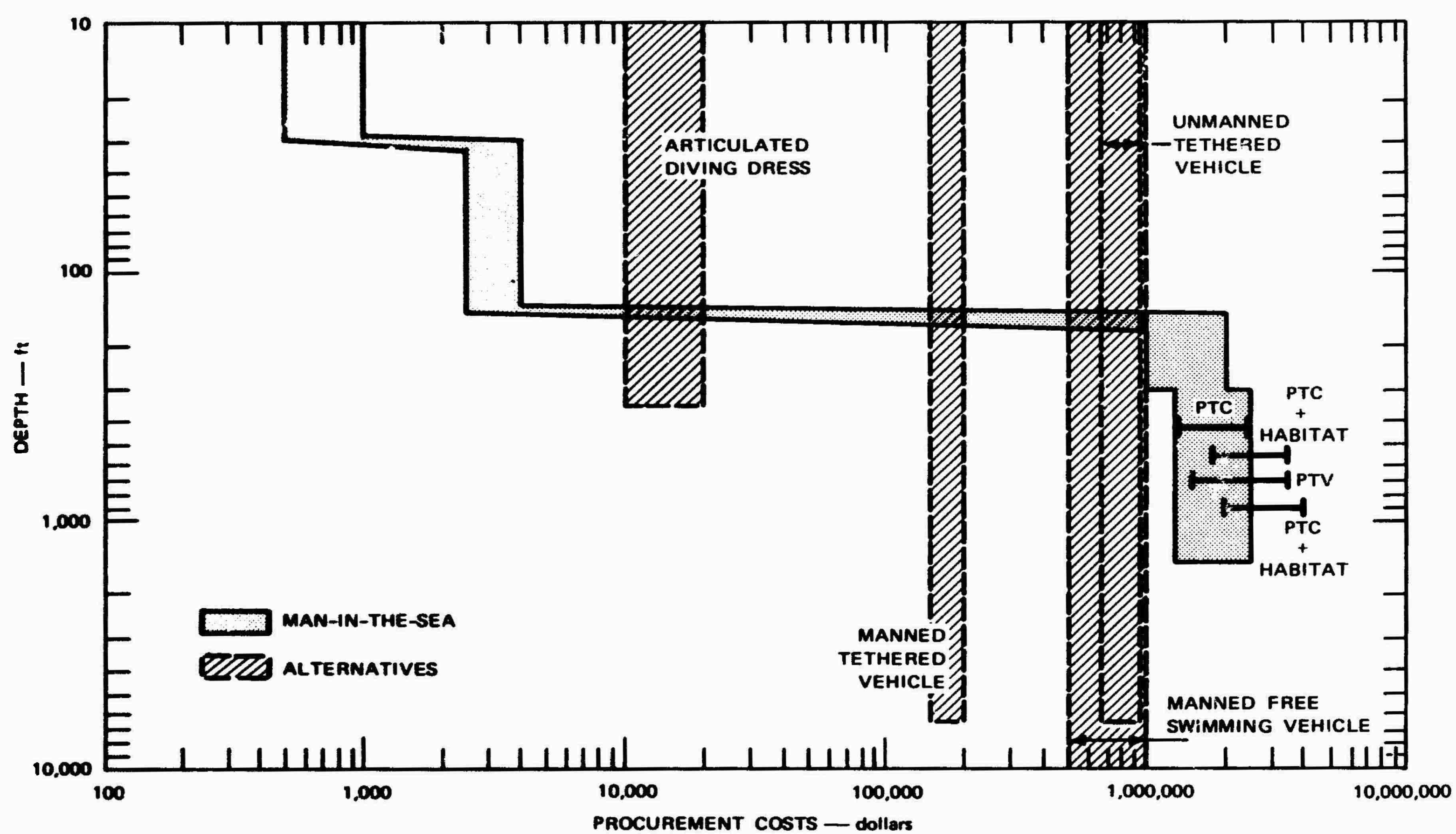


FIGURE VI-2 COMPARISON OF SYSTEMS INVESTMENT COSTS FOR SMALL OBJECT RECOVERY OPERATION (SUPPORT VESSEL COSTS NOT INCLUDED)

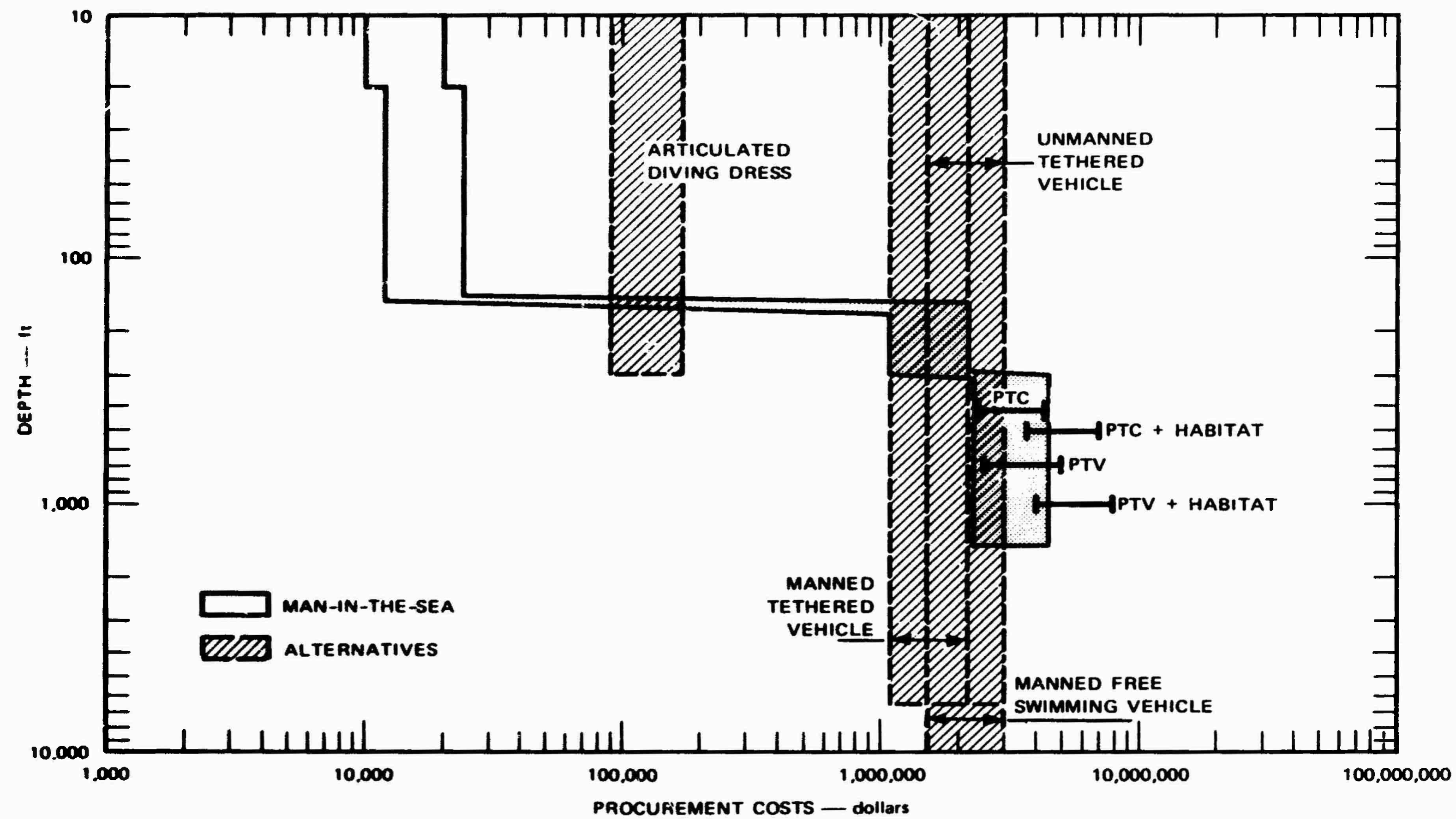


FIGURE VI-3 COMPARISON OF SYSTEMS INVESTMENT COSTS FOR SMALL OBJECT RECOVERY OPERATION (SUPPORT VESSEL COSTS INCLUDED)

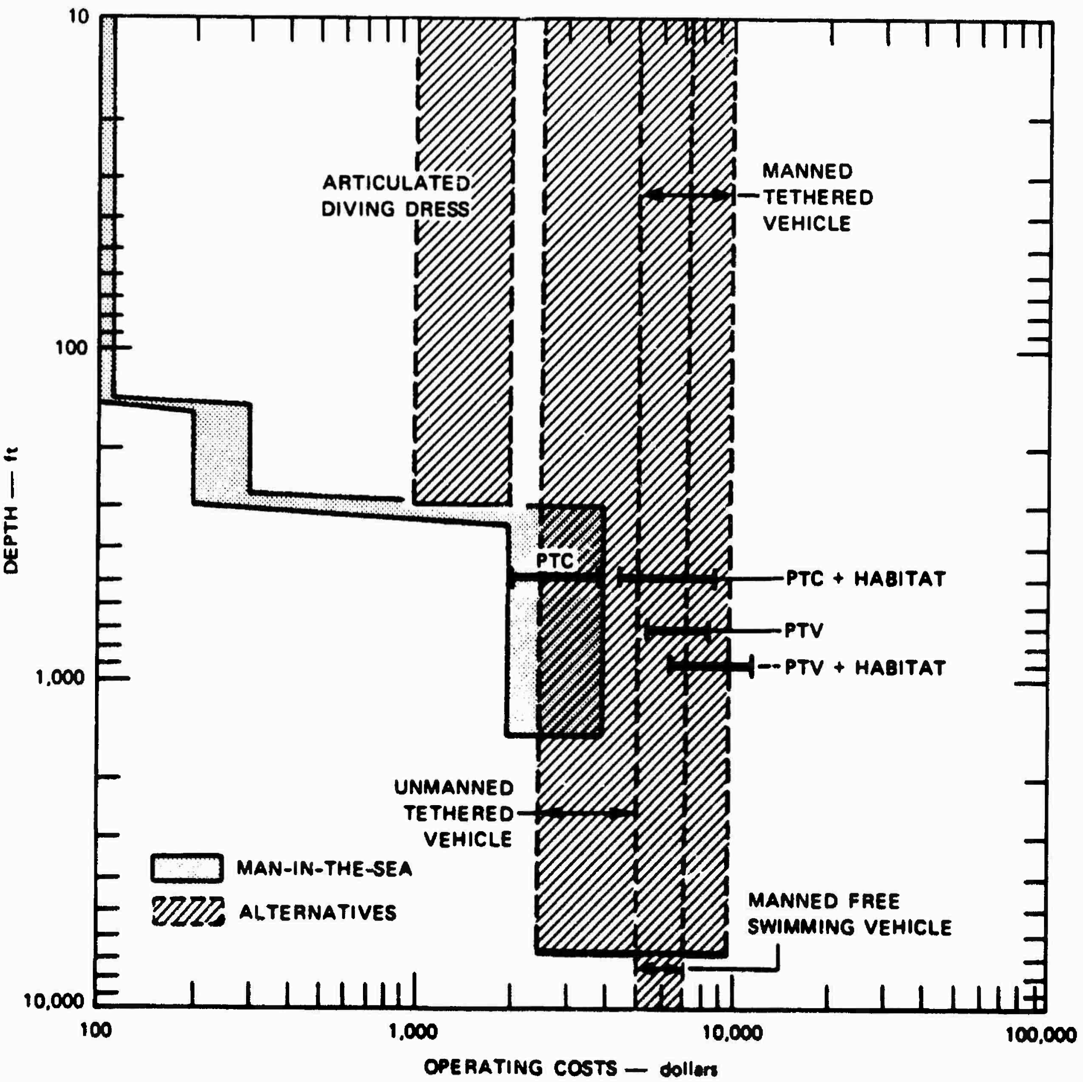


FIGURE VI-4 COMPARISON OF SYSTEMS OPERATING COSTS FOR SMALL OBJECT RECOVERY OPERATION (SUPPORT VESSEL COSTS NOT INCLUDED)

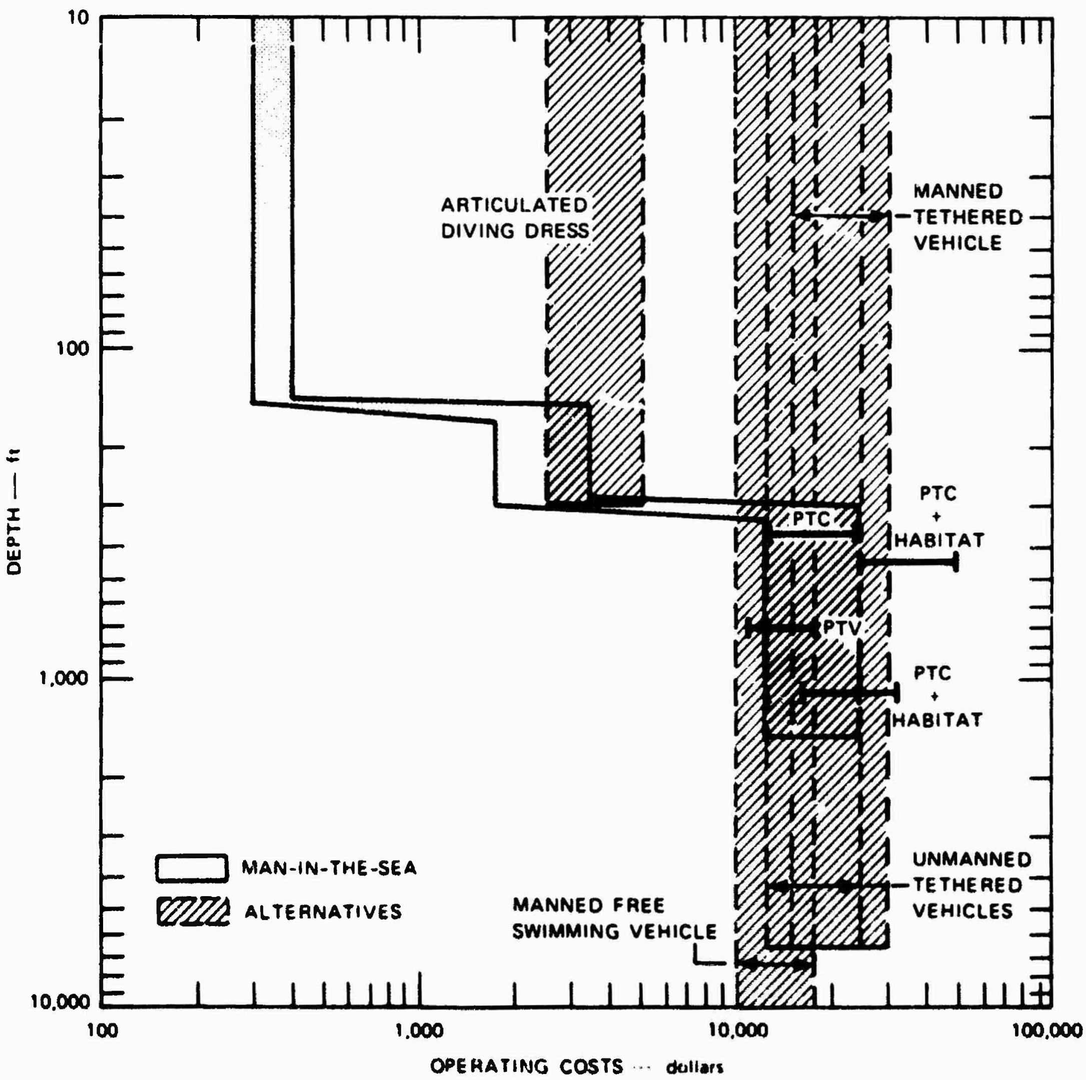


FIGURE VI-5 COMPARISON OF SYSTEMS OPERATING COSTS FOR SMALL OBJECT RECOVERY OPERATION (SUPPORT VESSEL COSTS INCLUDED)

C. Cost Comparison For Aircraft Salvage Operation

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1. MAN-IN-THE-SEA Systems Options

MAN-IN-THE-SEA systems options selected for aircraft salvage operations are shown in Table VI-7. The direct surface supported systems are separated into three depth regimes that reflect the differences in requirements for decompression facilities for air and mixed gas operations. The personnel transfer capsule augmented surface supported system is considered for both the surface-to-subsurface cycling operation and the surface-to-habitat operation. The latter is included for comparative purposes since, operationally, one would not consider using habitat for short duration operations. The mobile habitat, which eliminates the need for the PTC and surface decompression chamber, is included in this comparison.

A four-man work team was postulated for the operation. This constitutes a minimum size work team since it represents the operational allocation of two working personnel with two surface backup personnel.

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Table VI-7

MAN-IN-THE-SEA SYSTEMS OPTIONS AND COSTS FOR AIRCRAFT SALVAGE OPERATION

MAN-IN-THE-SEA Systems Options			Operational Life Support Components						Personnel Life Support Components		Support Vessel	
Category	Applicable Depth Regime	Breathing Mixture	Decompression Facilities		Personnel Transfer Capsule (PTC)		Habitat		P $/man	O $/man day	P	O
			P	O	P	O	P	O				
Direct Surface Supported System	0-30 ft	Air							$1,000 / 500	< $ 10	3 tons $20,000 / 10,000	$30 / 20
	30-150 ft	Air	$3,000* / 2,000	< $ 10					↓	↓	↓	↓
	150-300 ft	Mixed $He-N_2-O_2$	$2,000,000 / 1,000,000	$200 / 100					$5,000 / 3,000	$30 / 20	50 tons $150,000 / 80,000	$300 / 150
Augmented Surface Supported System (PTC)	300 ft	Mixed $He-N_2-O_2$	↓	↓	$500,000 / 300,000	$200 / 100			↓	↓	500 tons $2,000,000 / 1,000,000	$2,000 / 1,000
	300 ft	Mixed $He-N_2-O_2$	↓	↓	↓	↓	$1,000,000 / 500,000	$500 / 250	↓	↓	1,000 tons $4,000,000 / 2,000,000	$4,000 / 2,000
Self-Contained Mobile Habitat	300 ft	Mixed $He-N_2-O_2$					$1,500,000 / 750,000	$500 / 250	↓	↓	50 tons $150,000 / 80,000	$300 / 150

P - Procurement cost
O - Operating cost $/day
* High cost estimate / Low cost estimate

2. Alternative Systems Options

Work system alternatives to MAN-IN-THE-SEA systems selected for small object recovery operations are shown in Table VI-8. The systems options, all supported by surface platforms, are the following:

- Manned free swimming vehicles such as the ALVIN, AUTEC, or BEAVER MARK IV
- Manned tethered vehicle such as the GUPPY
- Manned tethered vehicle such as the ARTICULATED DIVING DRESS.

Table VI-8

ALTERNATIVE SYSTEMS OPTIONS AND COSTS

System Options		Vehicle Cost		Support Vessel Cost	
Category	Examples	Procurement	Operating ($/day)	Procurement	Operating ($/day)
Manned free vehicles	ALVIN, AUTEC, BEAVER	$1,000,000* 500,000	$1,500 1,000	500 tons** $2,000,000 1,000,000	$2,000 1,000
Manned tethered vehicle	ARTICULATED DIVING DRESS (300 ft max)	$ 20,000 10,000	$ 200 100	50 tons $ 150,000 80,000	$ 300 150
	GUPPY	$ 200,000 150,000	$1,000 500	500 tons $2,000,000 1,000,000	$2,000 1,000

* High cost estimate / Low cost estimate

** Surface support vessel displacement

3. Task-Time Distributions

The task-time distribution for aircraft salvage operation is shown in Tables VI-9 through VI-12. The detailed task analysis for the aircraft salvage operation is presented in Appendix A. It should be noted that the aircraft salvage operation as shown in the task-time distribution does not include the search/locate time that was included in the small object recovery operation.

Tables VI-9 and VI-10 show the task-time distribution for MAN-IN-THE-SEA and alternative systems if the first technique of salvage is employed. The first technique described in Appendix A uses lifting mechanism for the recovery of the aircraft. Tables VI-11 and VI-12 show the task-time distribution for MAN-IN-THE-SEA and alternative systems if the second technique of salvage is employed. The second technique, also described in Appendix A, uses buoyant lift concept, in which foam is injected into the aircraft for recovery. The primary difference between Technique I and Technique II of aircraft salvage operation is in the demands for manipulative capability of the work systems. Technique II requires less manipulative work.

Table VI-9

TASK-TIME DISTRIBUTION FOR AIRCRAFT SALVAGE OPERATION
(TECHNIQUE I): MAN-IN-THE-SEA SYSTEMS

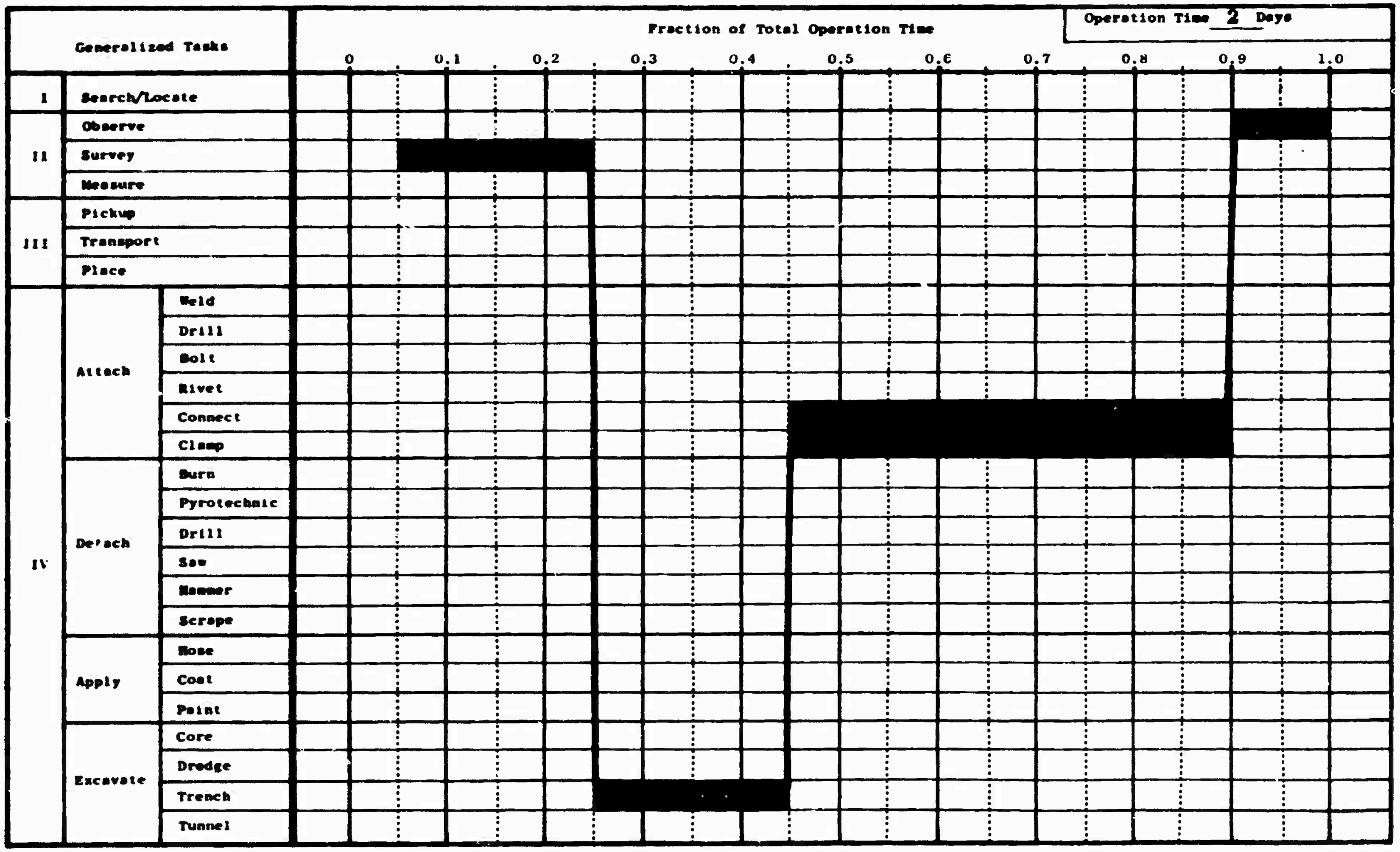


Table VI-10

TASK-TIME DISTRIBUTION FOR AIRCRAFT SALVAGE OPERATION
(TECHNIQUE I): ALTERNATIVE SYSTEMS

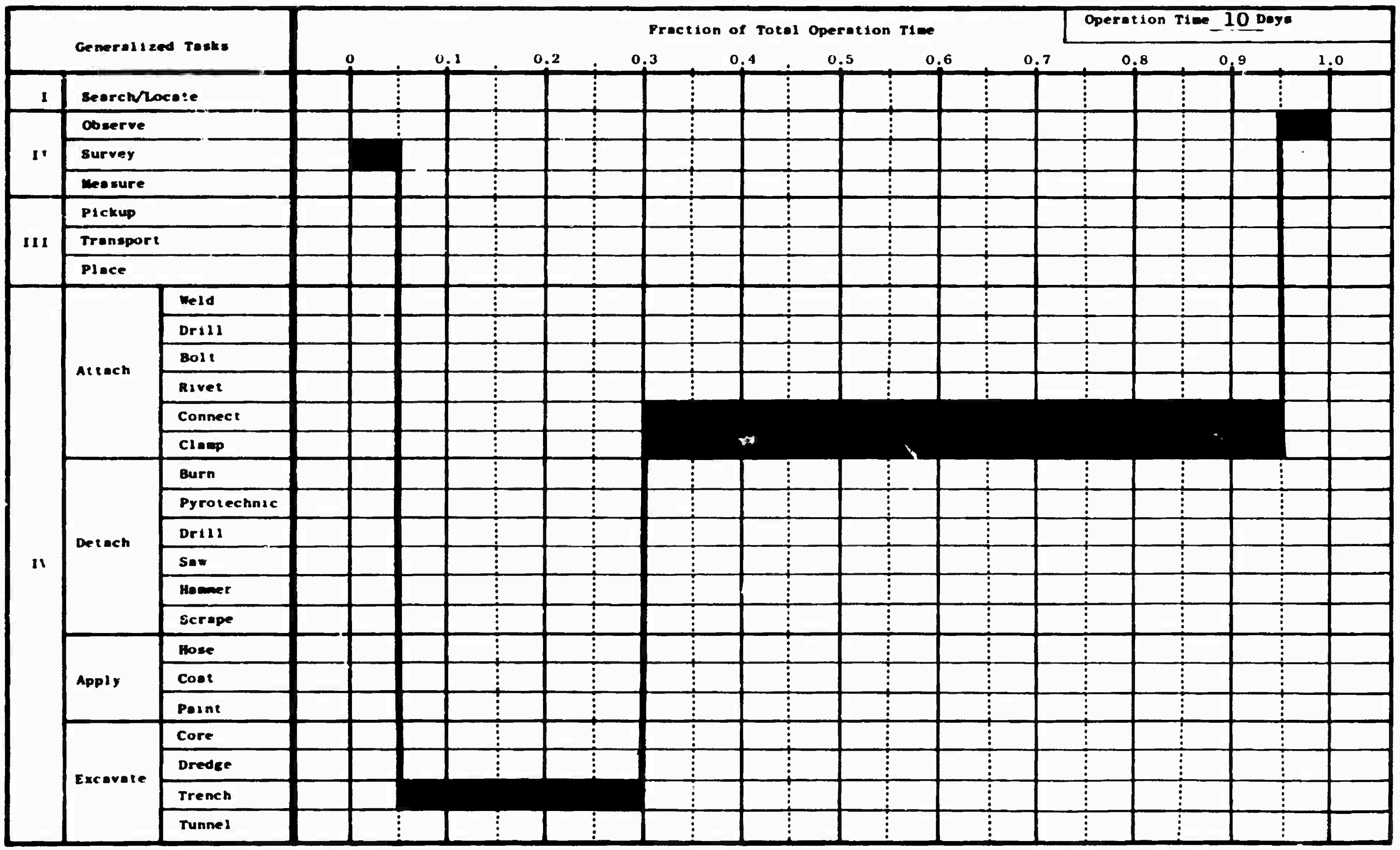


Table VI-11

TASK-TIME DISTRIBUTION FOR AIRCRAFT SALVAGE OPERATION
(TECHNIQUE II): MAN-IN-THE-SEA SYSTEMS

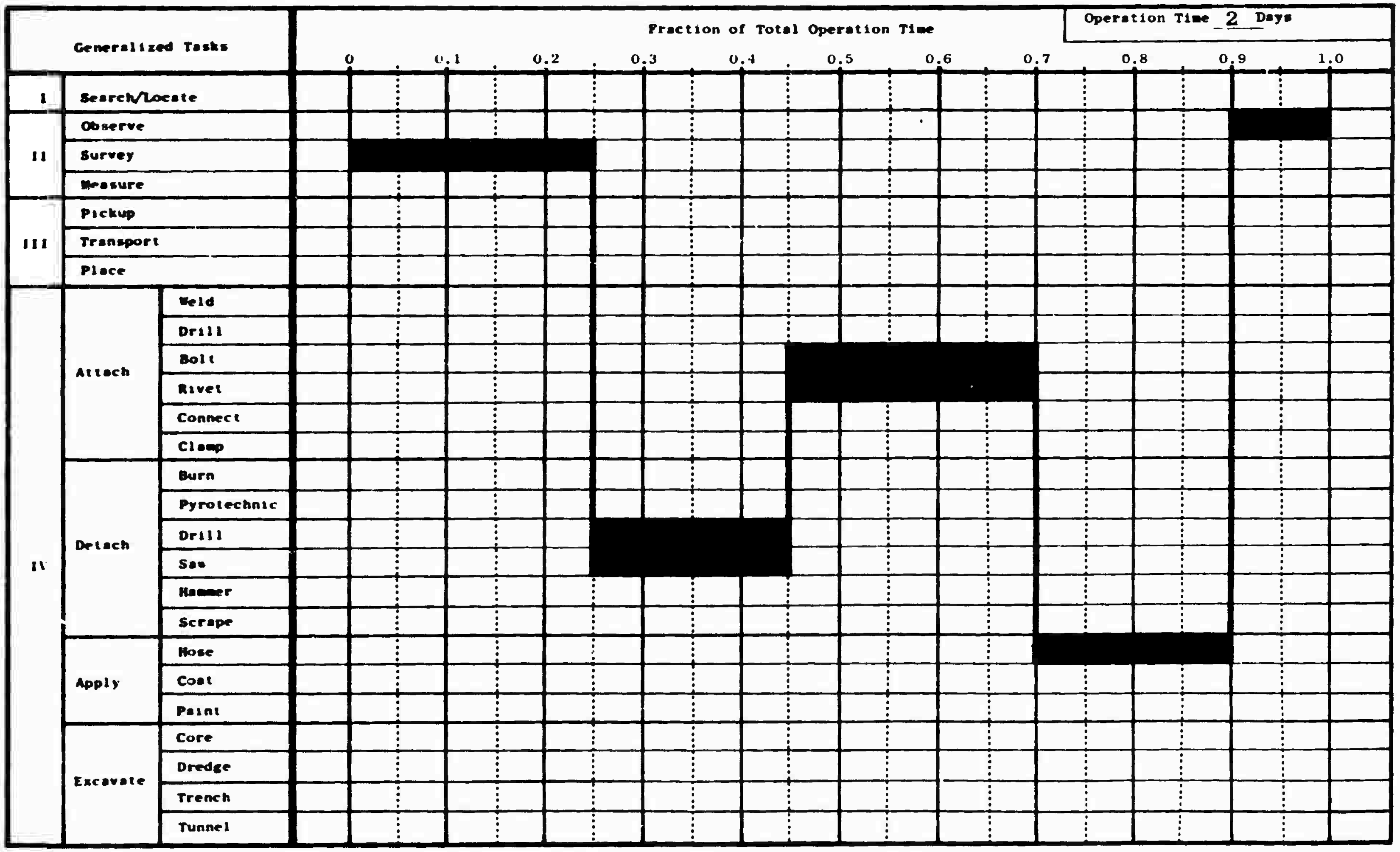
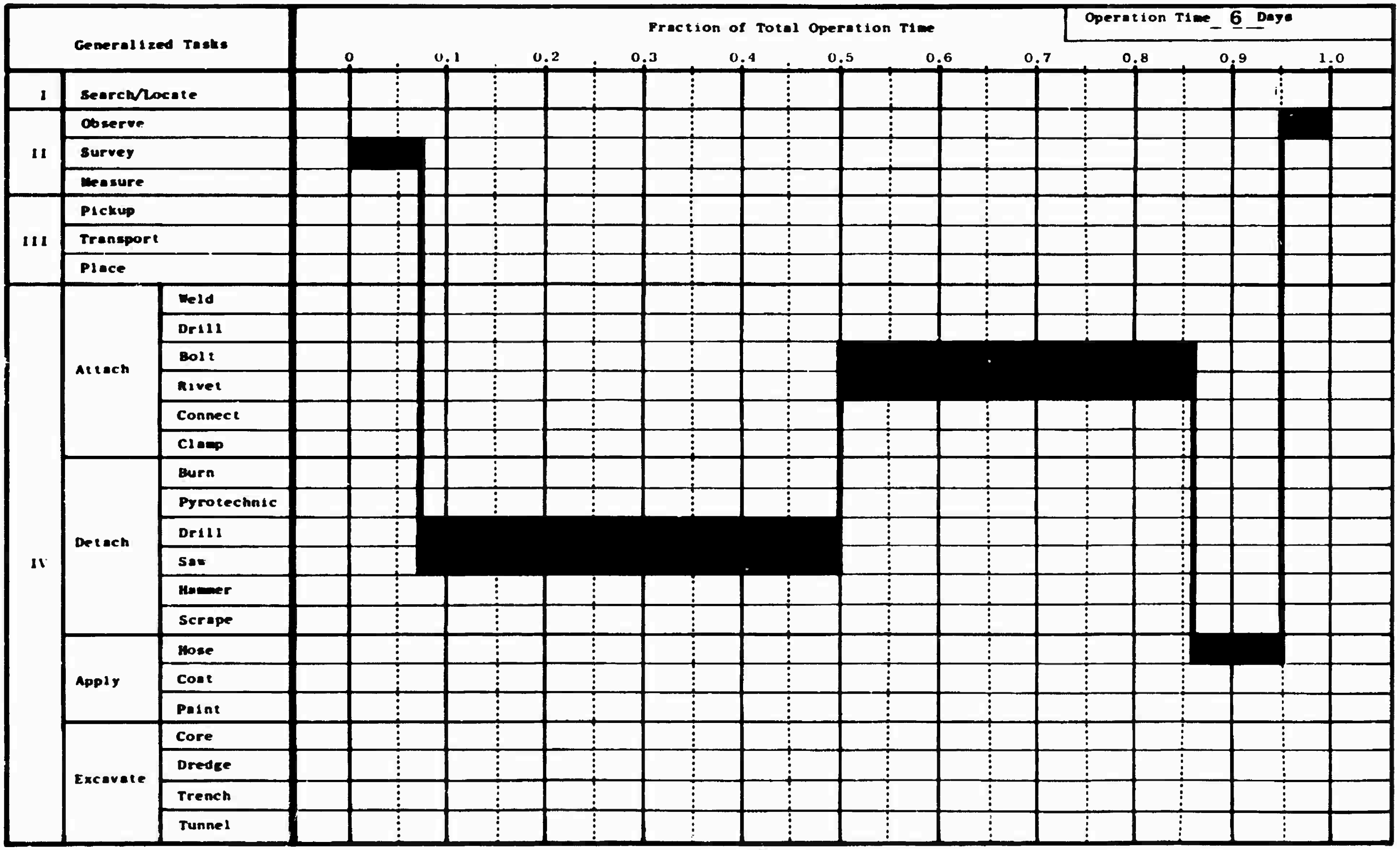


Table VI-12

TASK-TIME DISTRIBUTION FOR AIRCRAFT SALVAGE OPERATION
(TECHNIQUE II): ALTERNATIVE SYSTEMS



4. Aircraft Salvage Operation Cost Comparison Summary

The comparison of work systems investment cost for aircraft salvage operation is the same as those shown in Figs. VI-2 and VI-3. Figure VI-2 compares the investment costs without the cost of the surface support ship. Figure VI-3 compares the investment costs where the surface support ship cost is included. A summary of investment cost comparison results follows:

- The dominant investment costs of the postulated systems for aircraft salvage operations are for the surface support vessel.
- For operating depths up to 150 ft MAN-IN-THE-SEA systems have definite investment cost advantages over alternative work systems. This advantage holds for the case where support vessel costs are not included and the case where support vessel costs are included.
- For depths up to 300 ft the ARTICULATED DIVING DRESS has the advantage in systems investment costs.
- For depths beyond 300 ft the MAN-IN-THE-SEA systems have investment costs comparable to alternative systems.

The comparison of work system operating costs for aircraft salvage operation is shown in Figs. VI-6 through VI-9. Figures VI-6 and VI-7 compare operating costs employing salvage Technique I. Figures VI-8 and VI-9 compare operating costs employing salvage Technique II. A summary of operating cost comparison results follows:

- MAN-IN-THE-SEA systems have an operating cost advantage over manned free swimming and tethered vehicles. This advantage exists for the entire MAN-IN-THE-SEA depth regime. This advantage is due entirely to the fact that man has a manipulative advantage over the vehicle systems.
- MAN-IN-THE-SEA systems have an operating cost advantage over the ARTICULATED DIVING DRESS within the depth capability of the diving dress.

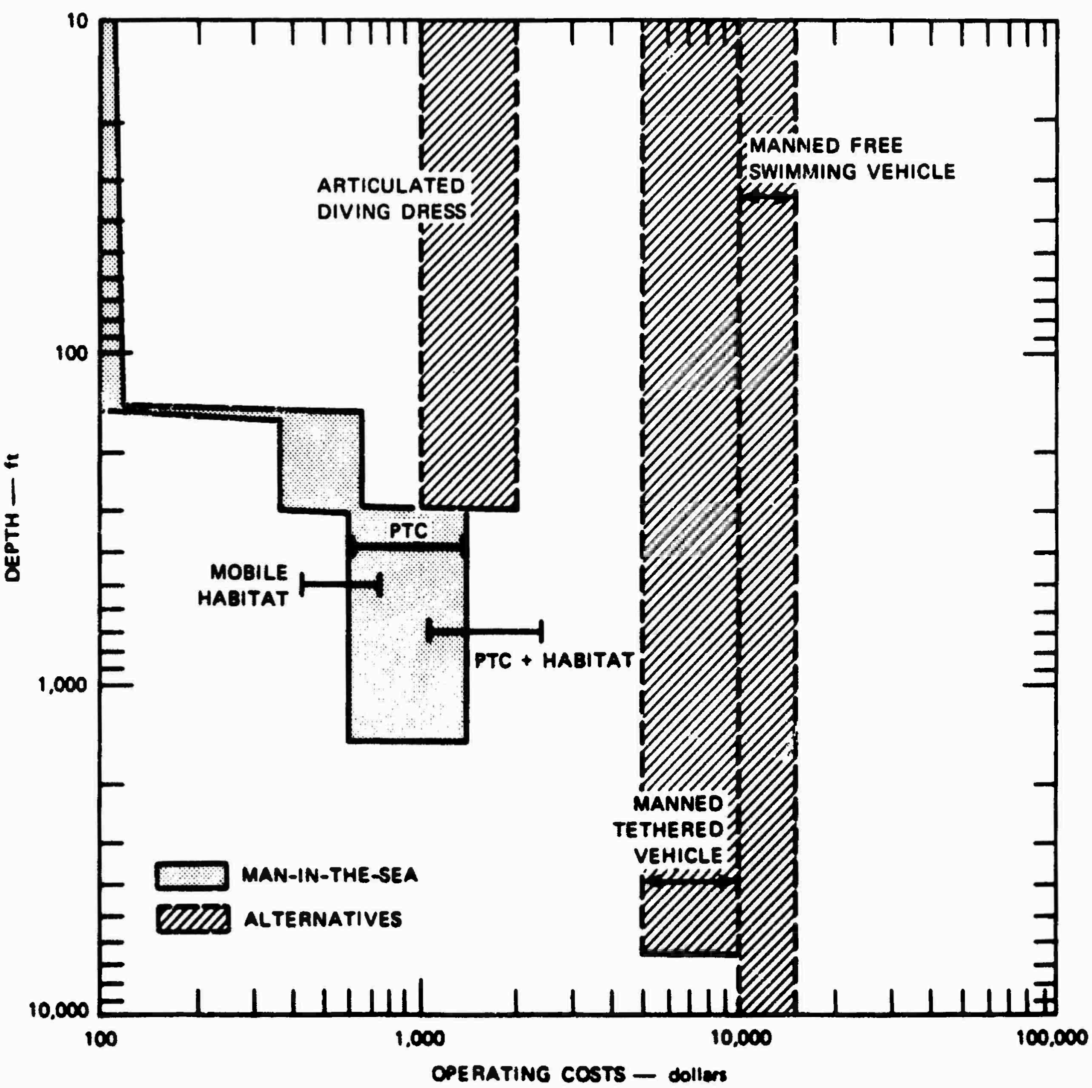


FIGURE VI-6 COMPARISON OF SYSTEMS OPERATING COSTS FOR AIRCRAFT SALVAGE OPERATION—TECHNIQUE I (SUPPORT VESSEL COSTS NOT INCLUDED)

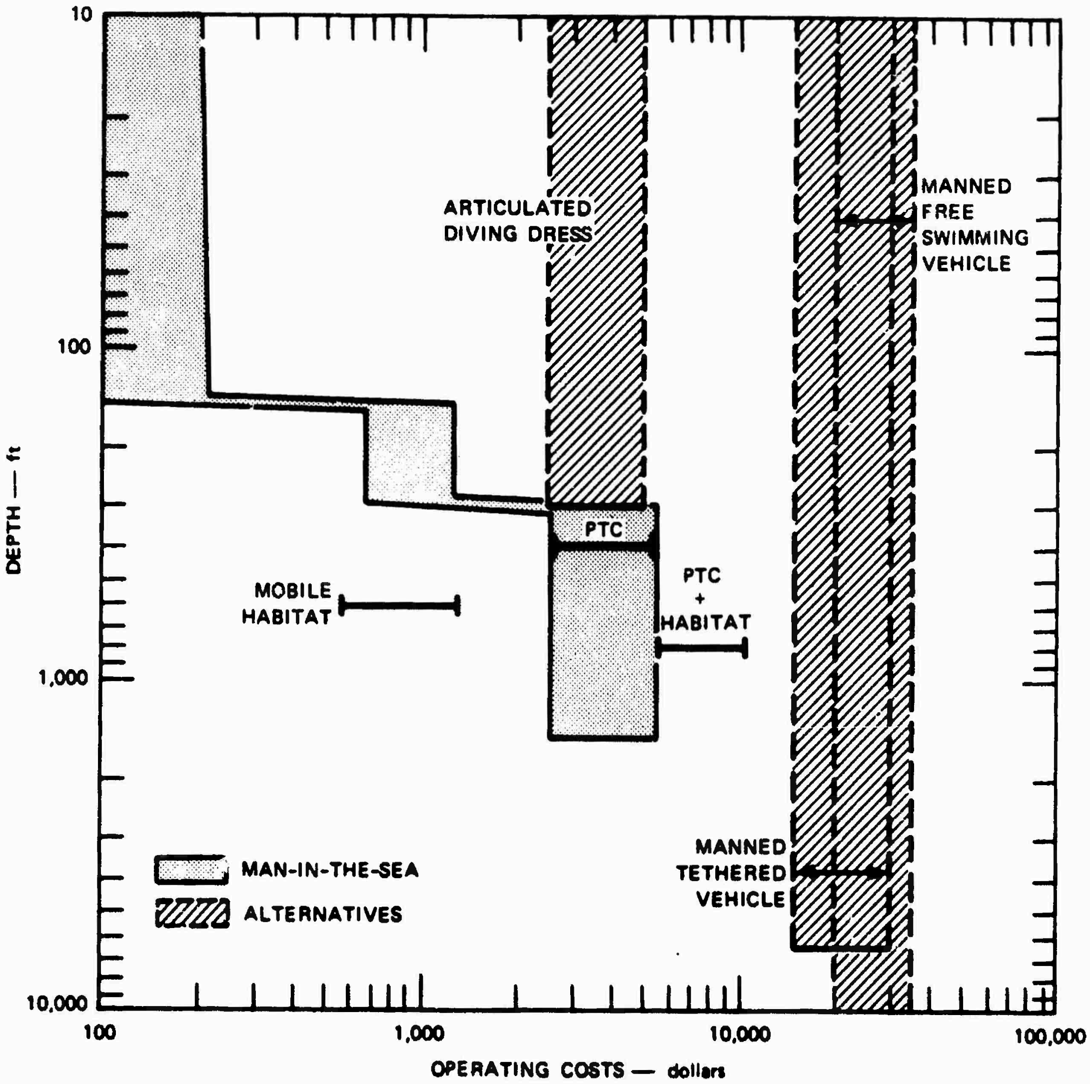


FIGURE VI-7 COMPARISON OF SYSTEMS OPERATING COSTS FOR AIRCRAFT SALVAGE OPERATION—TECHNIQUE I (SUPPORT VESSEL COSTS INCLUDED)

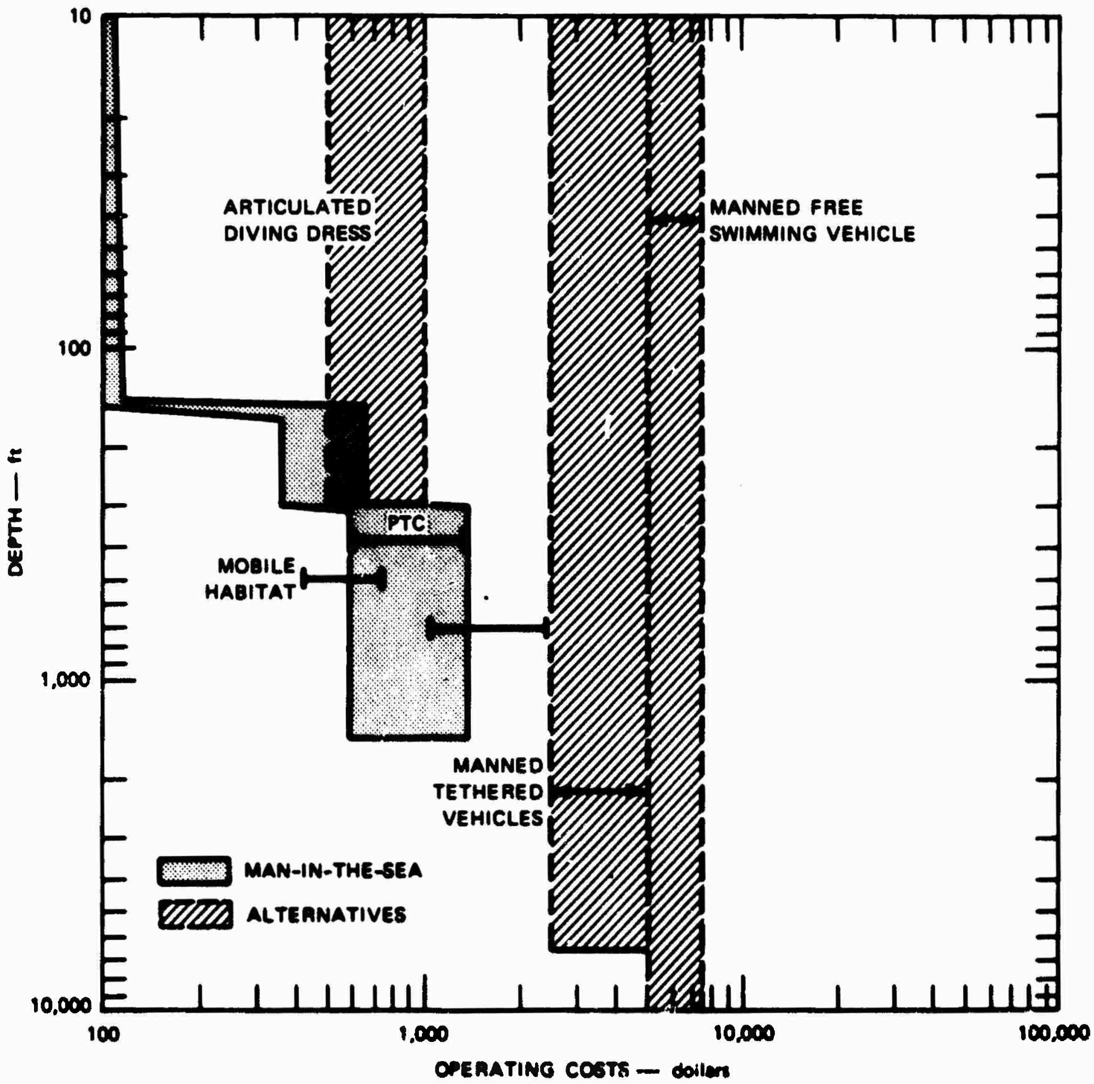


FIGURE VI-8 COMPARISON OF SYSTEMS OPERATING COSTS FOR AIRCRAFT SALVAGE OPERATION—TECHNIQUE II (SUPPORT VESSEL COSTS NOT INCLUDED)

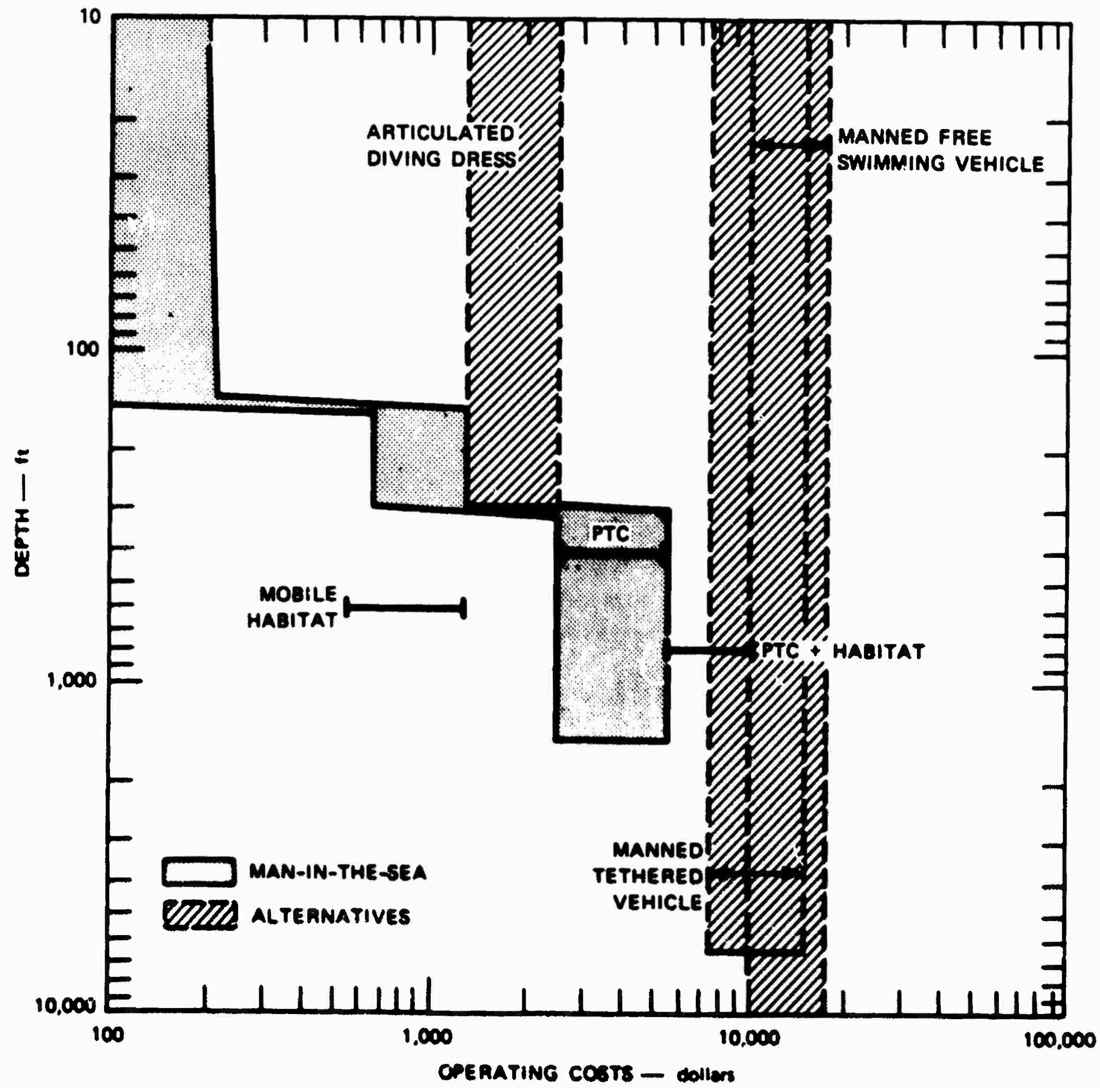


FIGURE VI-9 COMPARISON OF SYSTEMS OPERATING COSTS FOR AIRCRAFT SALVAGE OPERATION—TECHNIQUE II (SUPPORT VESSEL COSTS INCLUDED)

D. Cost Comparison For Ship Salvage Operation

1. <u>MAN-IN-THE-SEA Systems Options</u>

MAN-IN-THE-SEA systems options selected for ship salvage operations are the same as those used for the aircraft salvage operations. These systems options are shown in Table VI-7. The ship salvage operation, being a larger and more complex job, would require at least two minimum size (four-men) work teams. Therefore, two teams are used as the basis for cost comparison.

It was assumed that the two four-men work teams operating the "4 down--4 up" cycle can be supported by a single surface support vessel, such as those shown in Table VI-7.

2. Alternative Systems Options

Work system alternatives to MAN-IN-THE-SEA systems selected for ship salvage operations are the same as those used for the aircraft salvage operations. These systems options are shown in Table VI-8.

It was assumed for the purposes of this comparison that two free swimming vehicles can be deployed from a single support platform, as shown in Table VI-8. However, it was assumed that tethered vehicles must be operated off separate support platforms due to the operational difficulties inherent in the use of a tether.

3. Task-Time Distributions

The task-time distribution of ship salvage operation is shown in Tables VI-13 and VI-14. The detailed task analysis for the ship salvage operation is presented in Appendix A. As in the aircraft salvage operation, the task-time distribution does not include the search/locate time.

Table VI-13 shows the task-time distribution as postulated for the MAN-IN-THE-SEA systems. The total MAN-IN-THE-SEA operation time is estimated to be 20 days. Table VI-14 shows the task-time distributions as postulated for the alternatives to MAN-IN-THE-SEA systems. The total alternative systems operation time is estimated to be 60 days. The primary reason for large time difference in operation time is the major requirements for the accomplishment of manipulative tasks.

Table VI-13

TASK-TIME DISTRIBUTION FOR SHIP SALVAGE OPERATION:
MAN-IN-THE-SEA SYSTEMS

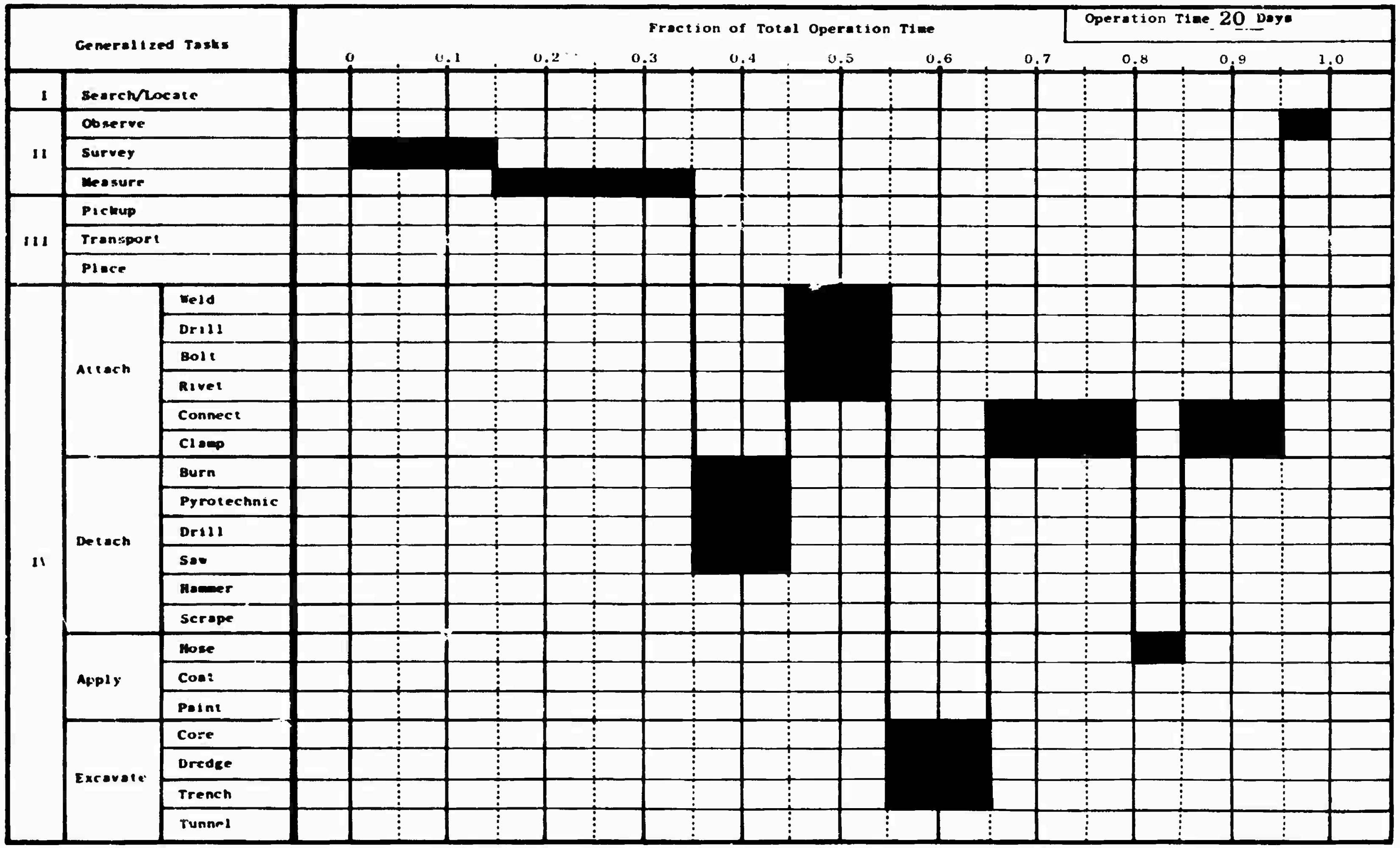
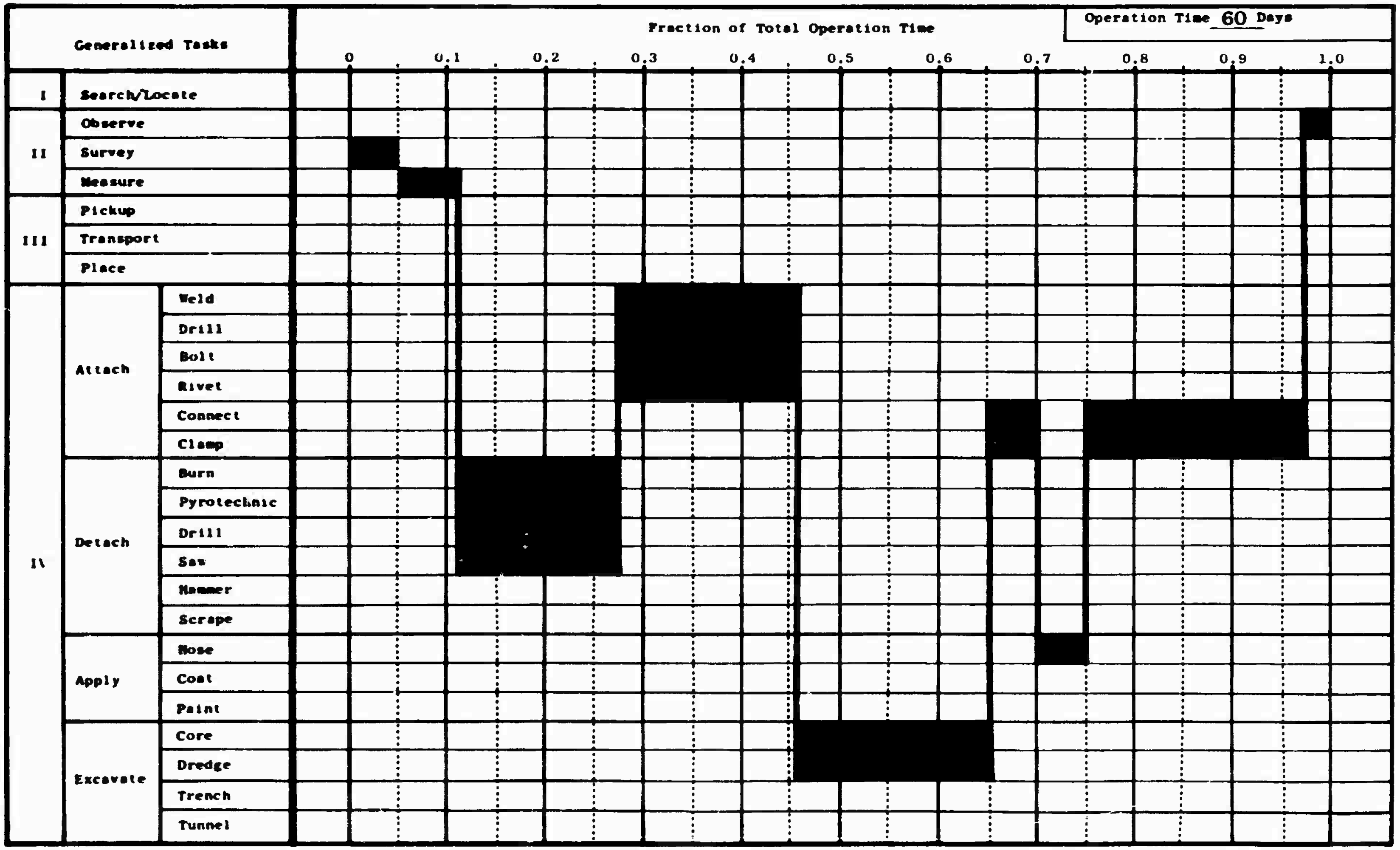


Table VI-14

TASK-TIME DISTRIBUTION FOR SHIP SALVAGE OPERATION: ALTERNATIVE SYSTEMS



4. Ship Salvage Operation Cost Comparison Summary

The comparison of work system investment costs for the ship salvage operation is shown in Figs. VI-10 and VI-11. A summary of investment cost comparison results follows:

- As in the previous cases examined, the dominant investment costs of work systems for ship salvage operations are for the surface support vessel.
- For operating depths up to 150 ft MAN-IN-THE-SEA systems have definite investment cost advantages over alternative work systems. This advantage holds for the case where support vessel costs are not included and the case where support vessel costs are included.
- For depths up to 300 ft the ARTICULATED DIVING DRESS has investment cost advantage.
- For depths beyond 300 ft MAN-IN-THE-SEA systems have comparable investment costs to alternatives where support vessel costs are not included. The exception is the case where the surface support vessel is not included for the manned tethered vehicle. In this instance the vehicle has the cost advantage.

The comparison of work system operating costs for the ship salvage operation is shown in Figs. VI-12 and VI-13. In all cases MAN-IN-THE-SEA systems have an operating cost advantage over the alternatives. This advantage is due entirely to the fact that man has a manipulative advantage over the vehicle systems.

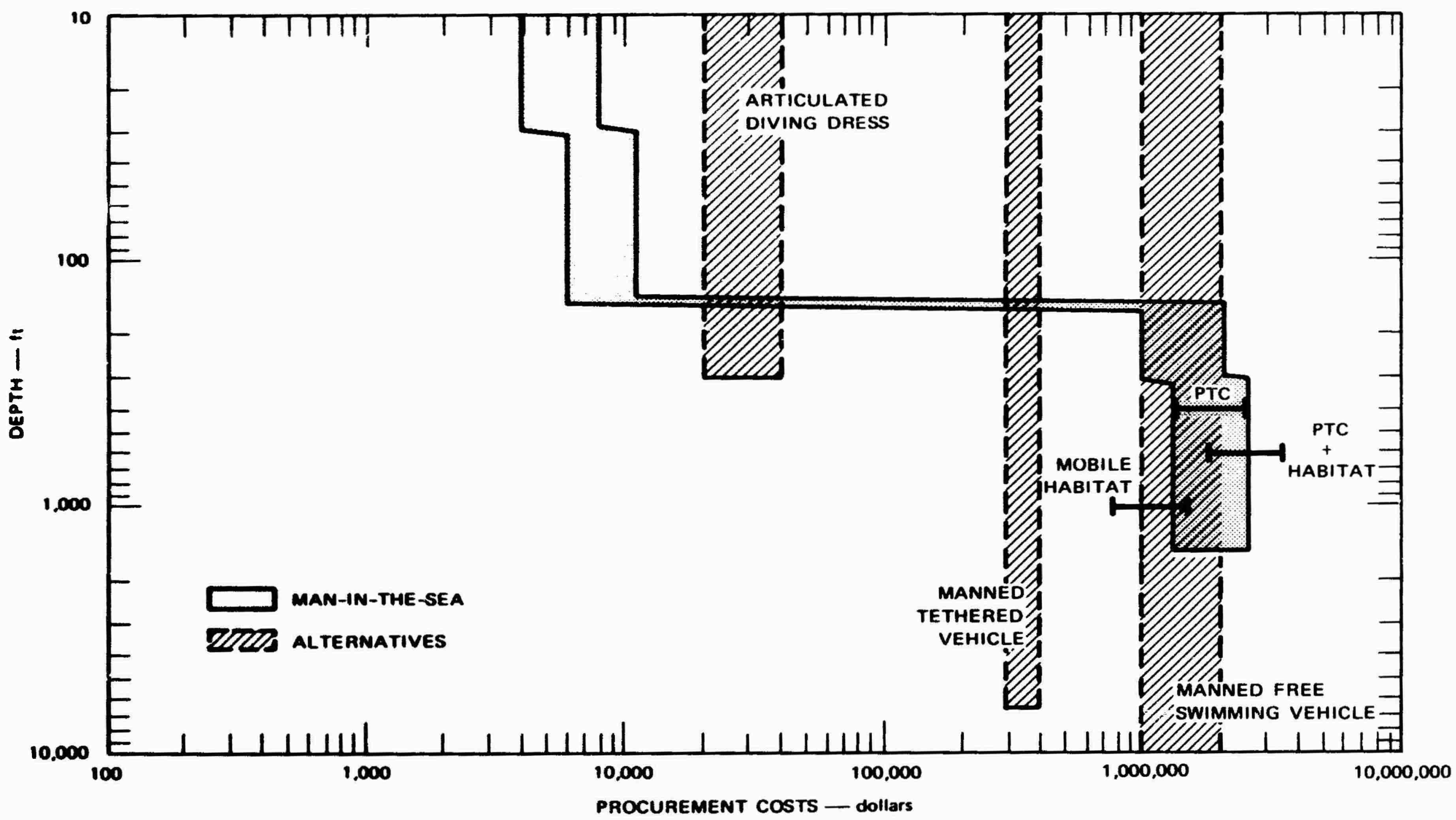


FIGURE VI-10 COMPARISON OF SYSTEMS INVESTMENT COSTS FOR SHIP SALVAGE OPERATION (SUPPORT VESSEL COSTS NOT INCLUDED)

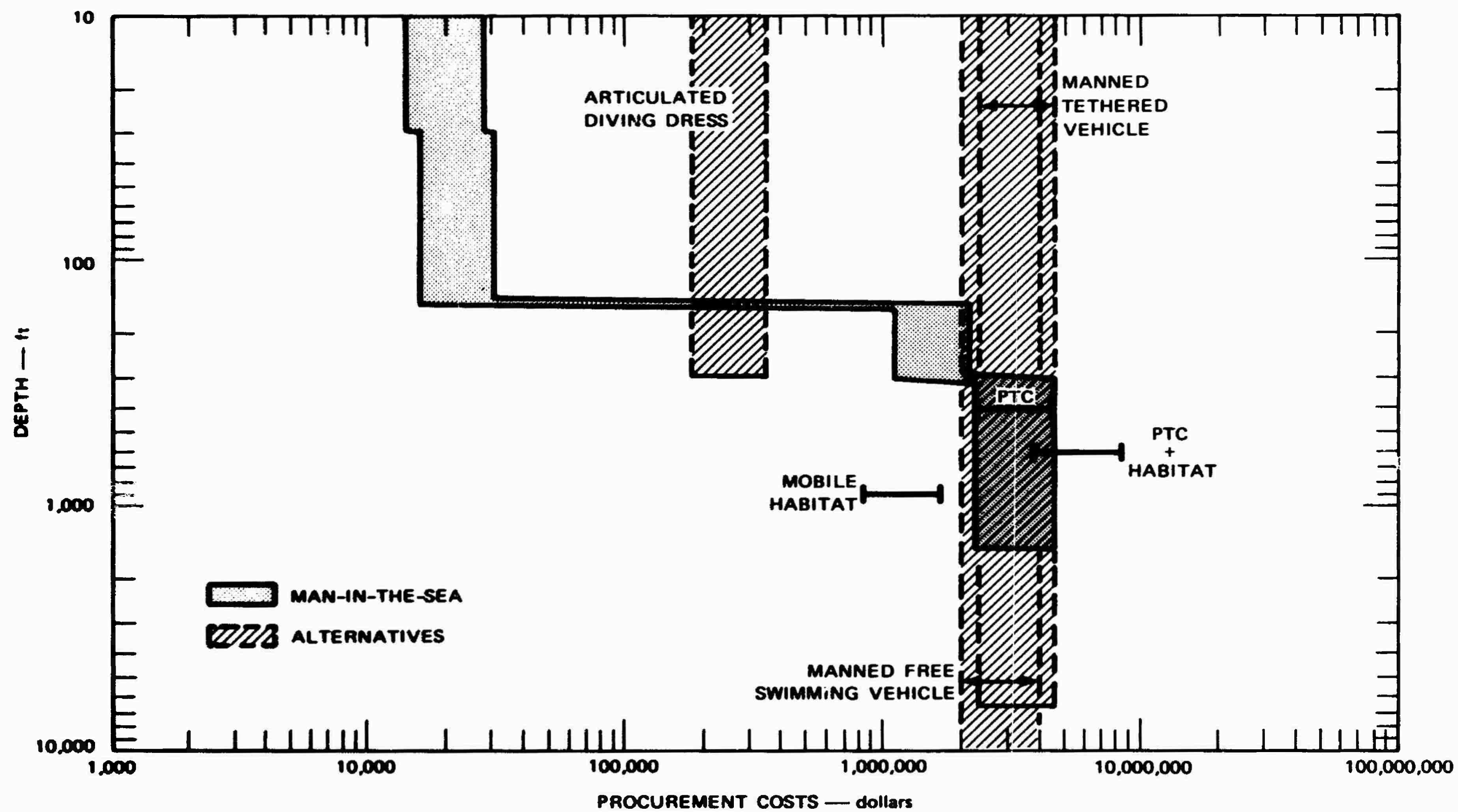


FIGURE VI-11 COMPARISON OF SYSTEMS INVESTMENT COSTS FOR SHIP SALVAGE OPERATION (SUPPORT VESSEL COSTS INCLUDED)

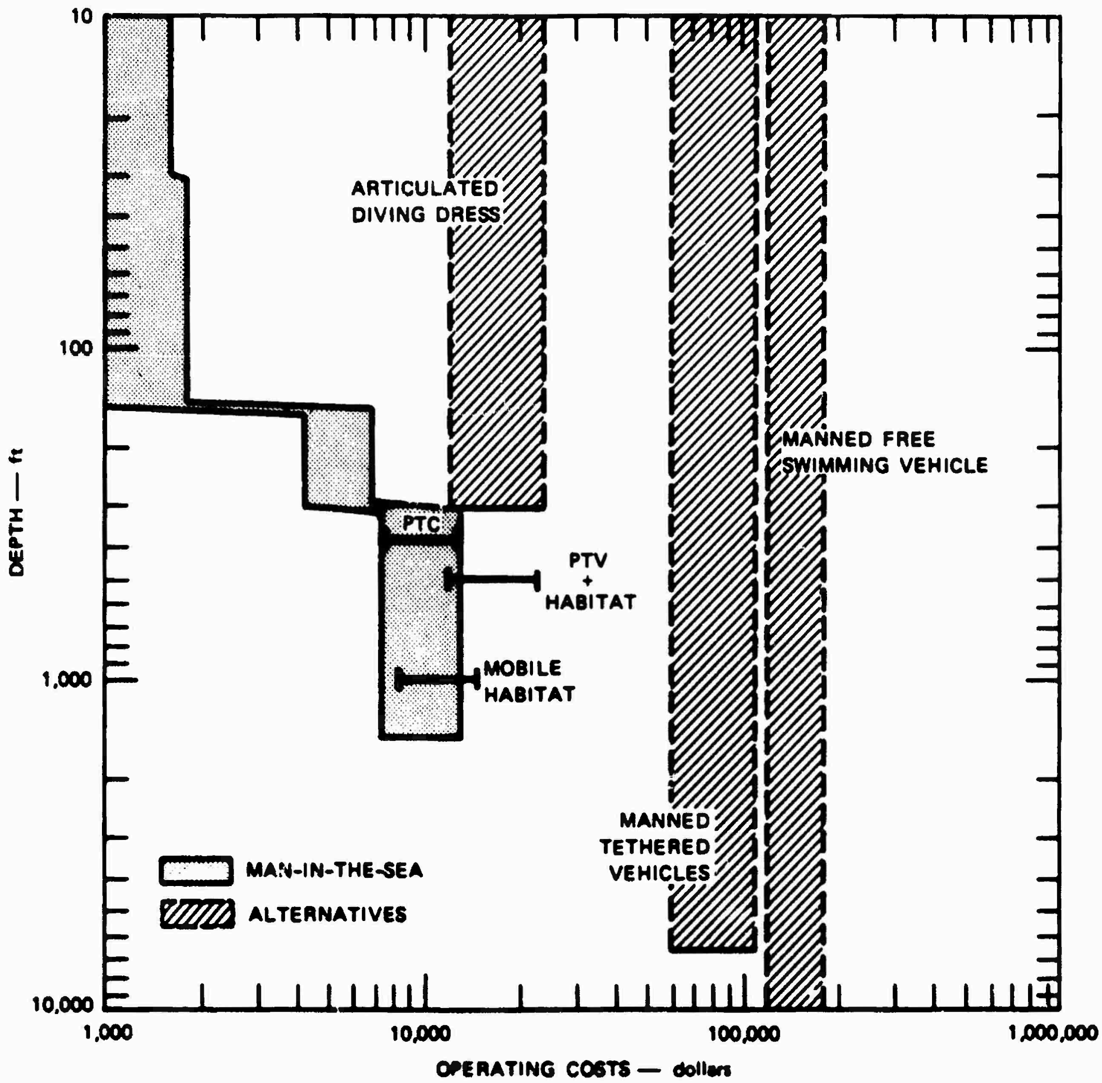


FIGURE VI-12 COMPARISON OF SYSTEMS OPERATING COSTS FOR SHIP SALVAGE OPERATION (SUPPORT VESSEL COSTS NOT INCLUDED)

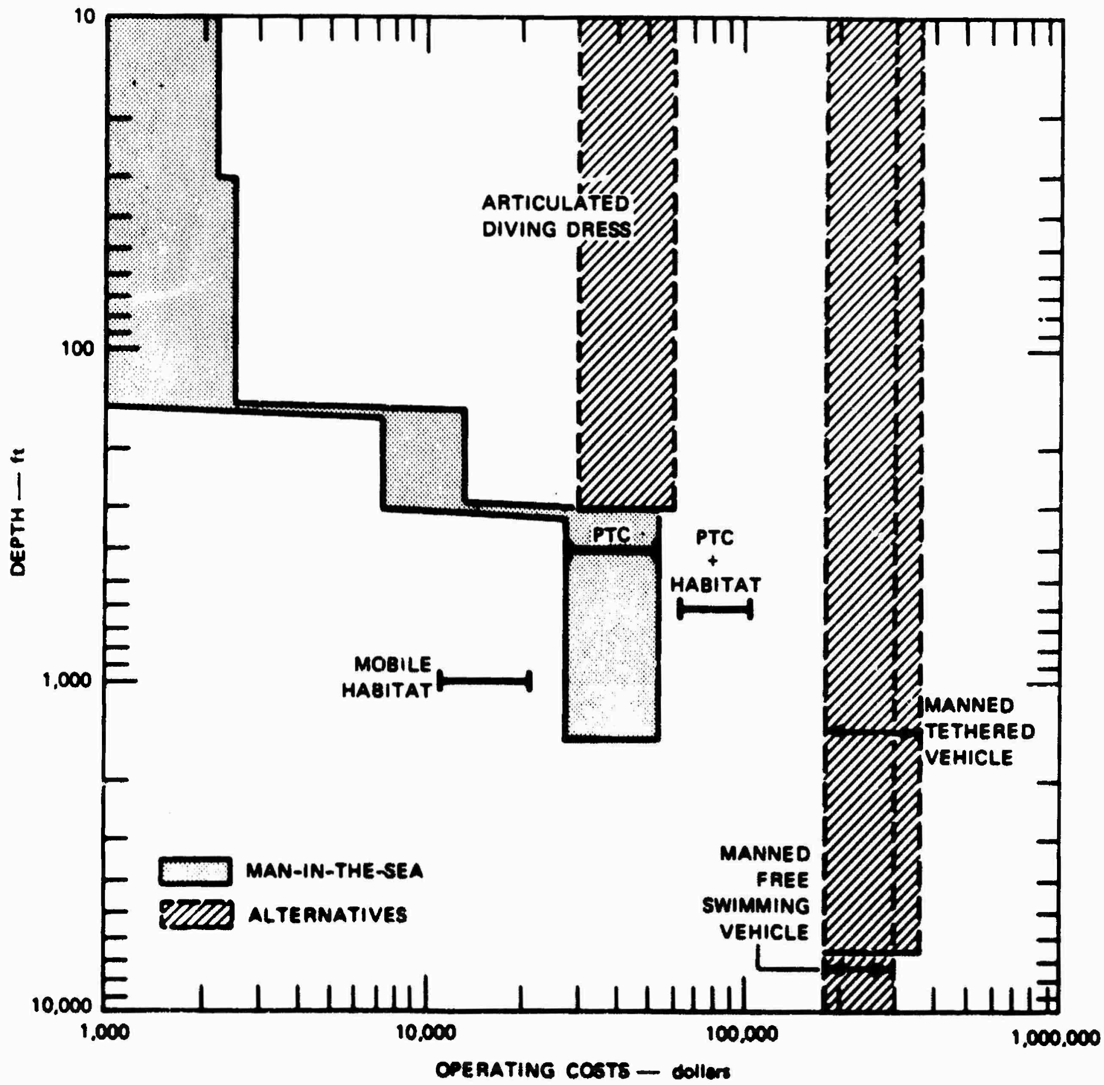


FIGURE VI-13 COMPARISON OF SYSTEMS OPERATING COSTS FOR SHIP SALVAGE OPERATION (SUPPORT VESSEL COSTS INCLUDED)

E. Cost Comparison For Simple Undersea Construction Operation

1. MAN-IN-THE-SEA Systems Options

MAN-IN-THE-SEA systems options selected for the simple undersea construction operation are the same as those postulated for the aircraft salvage operation. The systems options are shown in Table VI-7. As in the earlier case, the direct surface supported systems are separated into three depth regimes that reflect the differences in requirements for decompression facilities in air and mixed gas operations. The personnel transfer capsule augmented surface supported system is considered for both the surface-to-subsurface cycling operation and the surface-to-habitat operation. The mobile habitat, which eliminates the need for the PTC and surface decompression chamber, is included in this comparison.

As in the aircraft salvage operation, a minimum size work team of four men was postulated.

2. Alternative Systems Options

Work system alternatives to MAN-IN-THE-SEA systems selected for the simple undersea construction operation are the same as those postulated for aircraft salvage operation. The systems options shown in Table VI-8 are the following:

- Manned free swimming vehicles
- Manned tethered vehicle such as the GUPPY
- Manned tethered vehicle such as the ARTICULATED DIVING DRESS.

3. Task-Time Distributions

The task-time distribution for the simple undersea construction operation is shown in Tables VI-15 and VI-16. The detailed task analysis for the simple undersea construction operation is presented in Appendix A.

Table VI-15 shows the task-time distribution as postulated for the MAN-IN-THE-SEA systems. The total MAN-IN-THE-SEA operation time is estimated to be 10 days. Table VI-16 shows the task-time distributions as postulated for the alternatives to MAN-IN-THE-SEA systems. The total alternative system operation time is estimated to be 12 days.

Table VI-15

TASK-TIME DISTRIBUTION FOR SIMPLE UNDERSEA CONSTRUCTION OPERATION:
MAN-IN-THE-SEA SYSTEMS

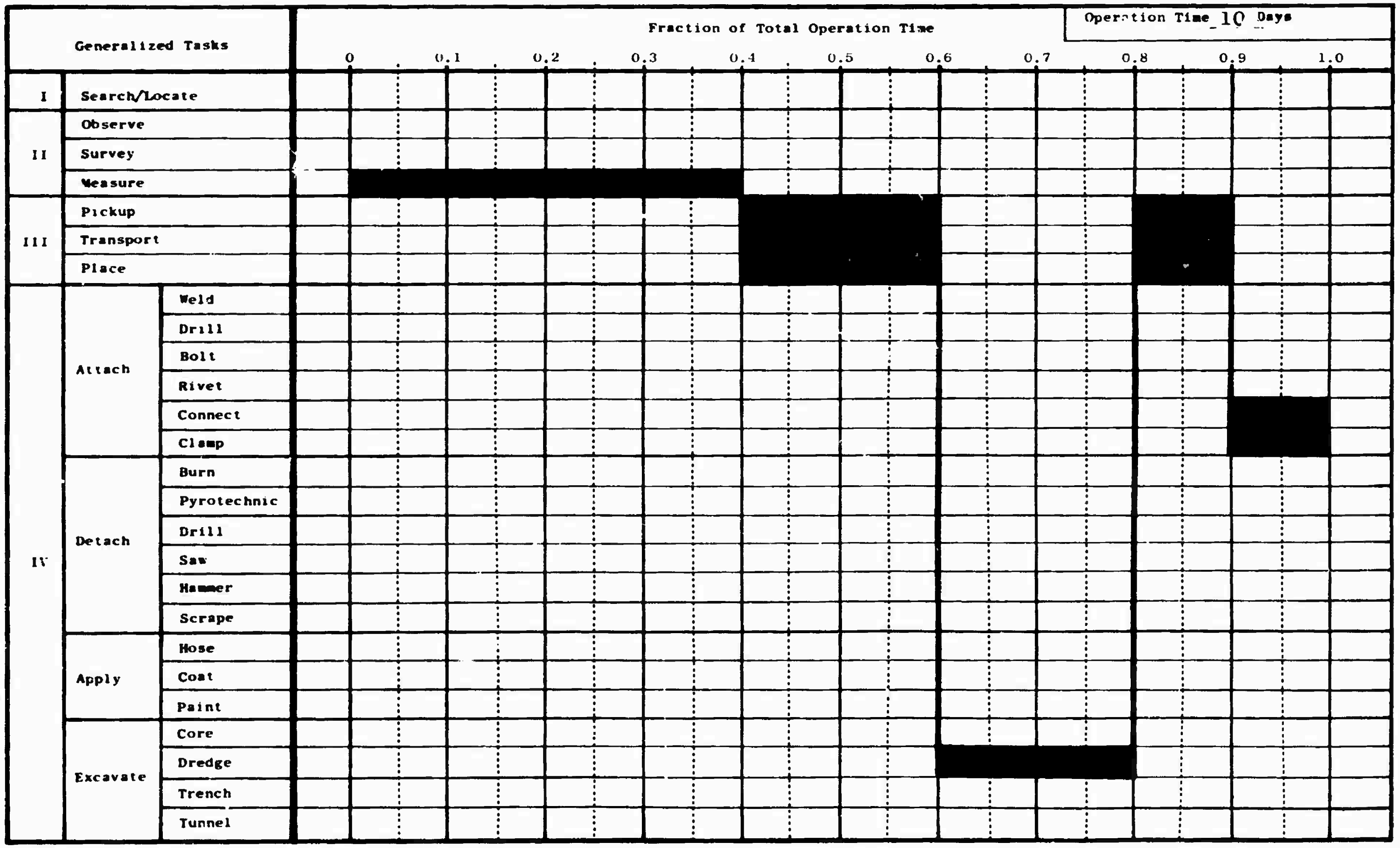
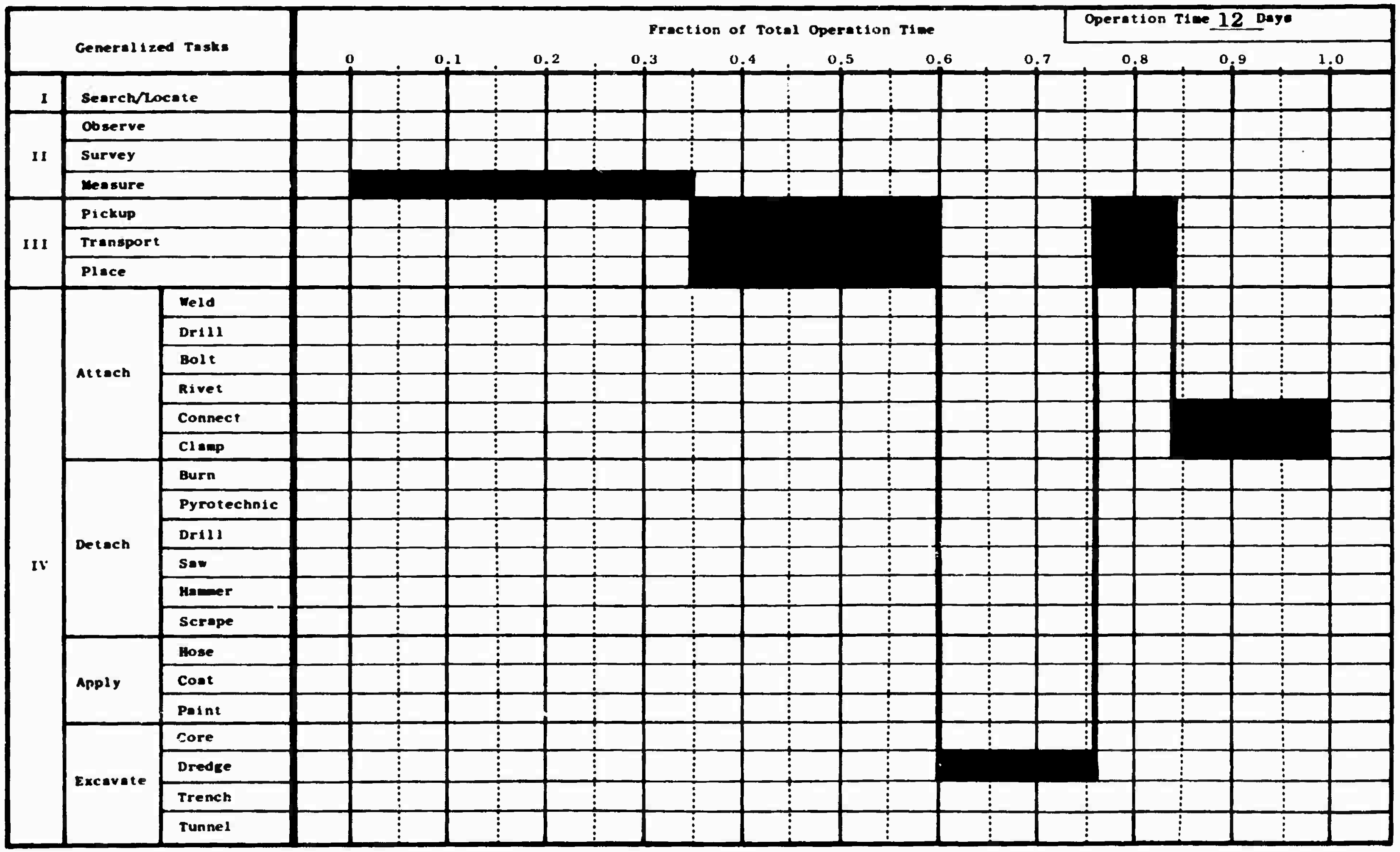


Table VI-16

TASK-TIME DISTRIBUTION FOR SIMPLE UNDERSEA CONSTRUCTION OPERATION: ALTERNATIVE SYSTEMS



4. Simple Undersea Construction Operation Cost Comparison Summary

Work system investment costs for the simple undersea construction operation is the same as that for the aircraft salvage operation and is shown in Figs. VI-10 and VI-11. The following is the summary of investment costs comparison results.

- The dominant investment costs of the postulated systems for simple undersea construction operation are for the surface support vessel.
- For operating depths up to 150 ft MAN-IN-THE-SEA systems have definite investment cost advantages over alternative work systems. This advantage holds for the case where support vessel costs are not included and the case where support vessel costs are included.
- For depths up to 300 ft the ARTICULATED DIVING DRESS has the advantage in system investment costs.
- For depths beyond 300 ft MAN-IN-THE-SEA systems have comparable investment costs to alternative systems.

The comparison of work systems operating costs for simple undersea construction operation is shown in Figs. VI-14 and VI-15. The following is a summary of the operating cost comparison results.

- For operating depths up to 150 ft MAN-IN-THE-SEA systems have a cost advantage over the alternative systems. This advantage is true for both cases where support vessel costs are and are not included.
- In the depth regime of 150-300 ft MAN-IN-THE-SEA and the ARTICULATED DIVING DRESS have comparable operating costs.
- For operating depths exceeding 300 ft MAN-IN-THE-SEA systems have a slight cost advantage over the alternatives if support vessel costs are not included. However, when support vessel costs are included, the PTC and PTC, plus habitat systems, have comparable costs to the alternatives. The exception is the mobile habitat system, which has a definite cost advantage over all other systems.

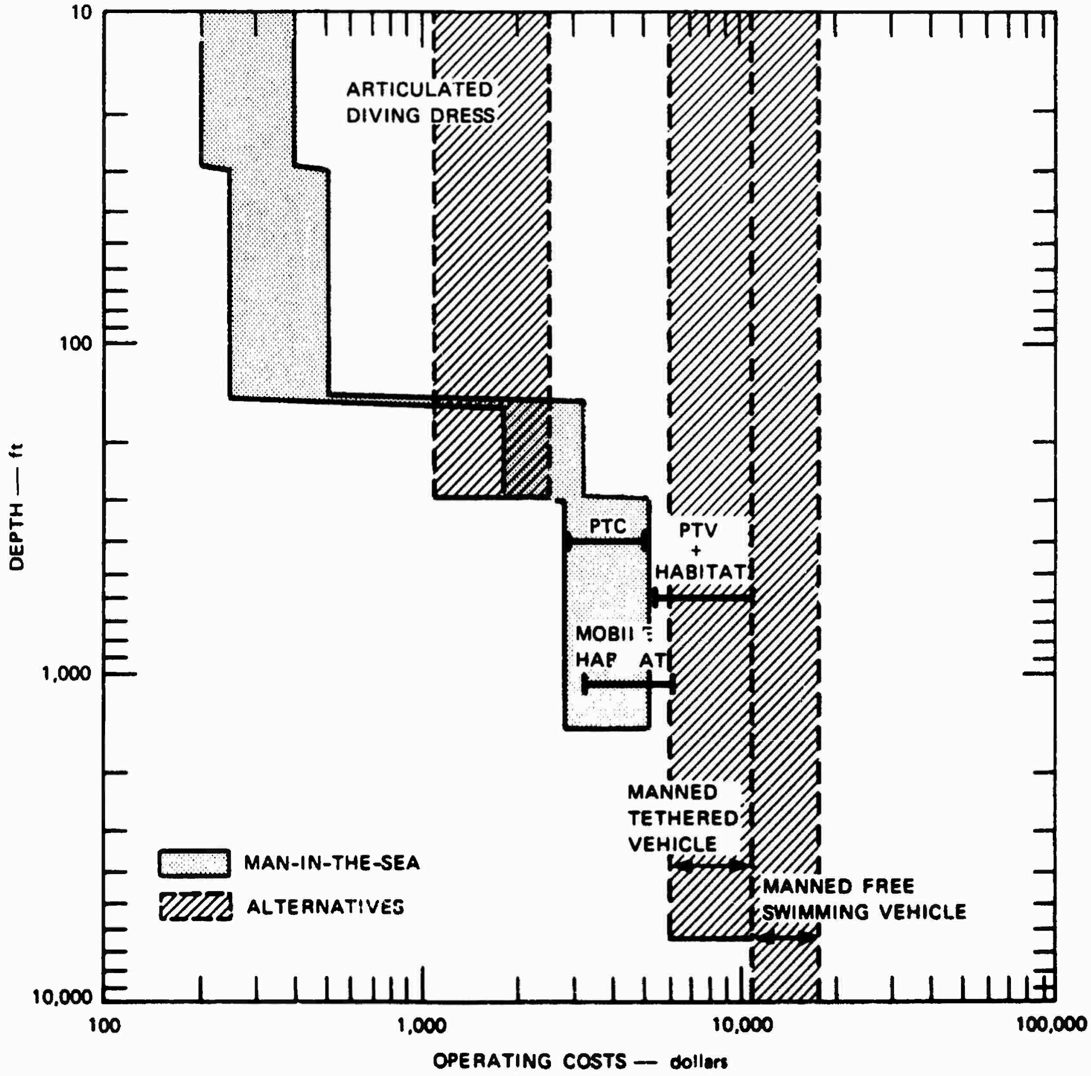


FIGURE VI-14 COMPARISON OF SYSTEMS OPERATING COSTS FOR SIMPLE UNDERSEA CONSTRUCTION OPERATION (SUPPORT VESSEL COSTS NOT INCLUDED)

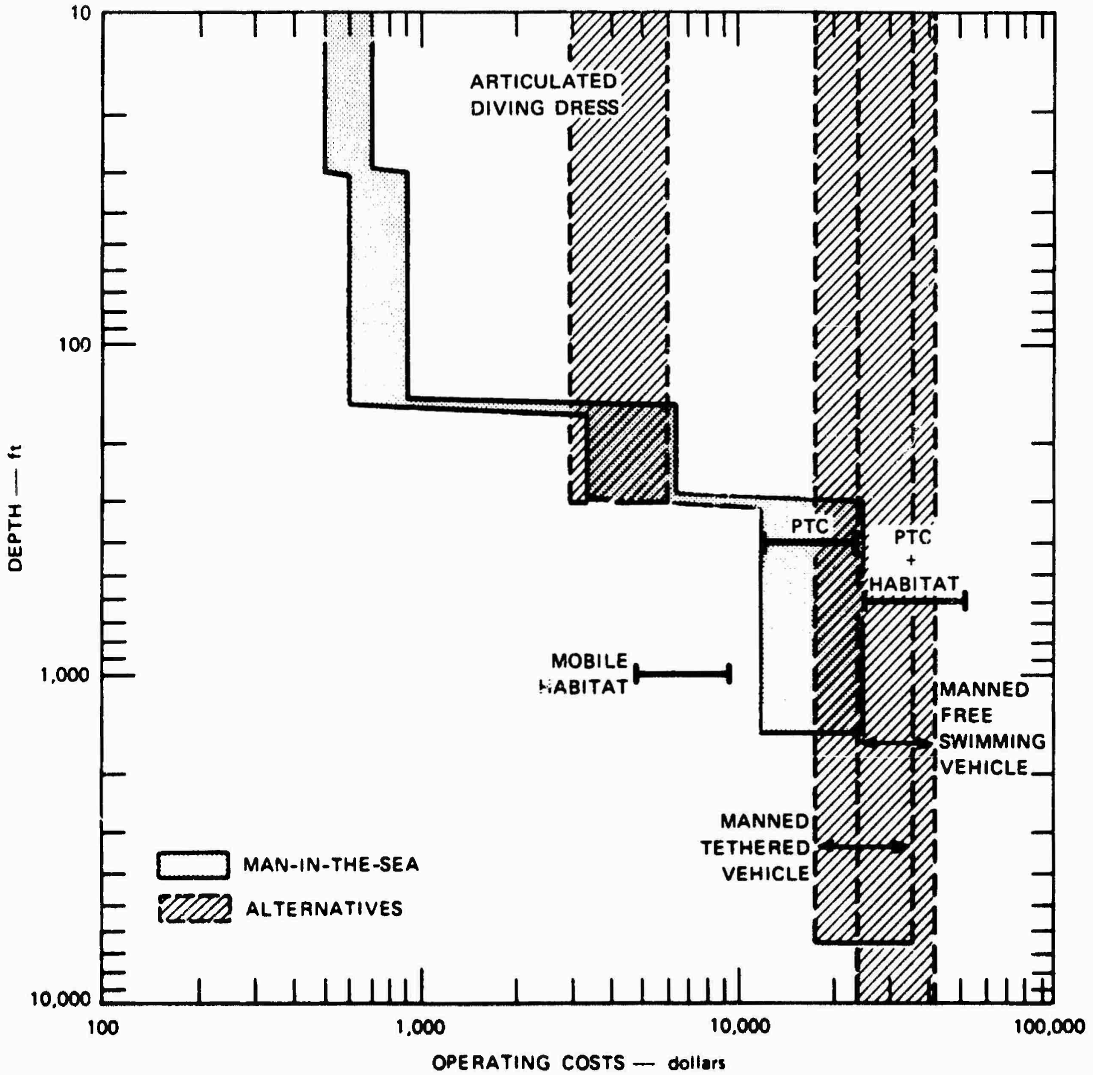


FIGURE VI-15 COMPARISON OF SYSTEMS OPERATING COSTS FOR SIMPLE UNDERSEA CONSTRUCTION OPERATION (SUPPORT VESSEL COSTS INCLUDED)

F. Cost Comparison For Undersea Facilities Construction Operation

1. MAN-IN-THE-SEA Systems Options

MAN-IN-THE-SEA systems options selected for the undersea facilities construction operation are the same as those postulated for the ship salvage operation. The systems options are shown in Table VI-7. Two four-men work teams were postulated as the basis for the cost comparison. It was assumed that the two four-men work teams operating in the "4 down--4 up" cycle can be supported by a single surface support vessel, such as those shown in Table VI-7.

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2. Alternative Systems Options

Work system alternatives to MAN-IN-THE-SEA systems selected for undersea construction operations are the same as those used for the ship salvage operations. These systems options are shown in Table VI-8. Two of each of the following systems are used:

- Manned free swimming vehicles
- Manned tethered vehicle such as the GUPPY
- Manned tethered vehicle such as the ARTICULATED DIVING DRESS

It was assumed for the purposes of this comparison that two free swimming vehicles can be deployed from a single support platform, as shown in Table VI-8. However, it was assumed that tethered vehicles must be operated from separate support platforms due to the operational difficulties inherent in the use of a tether.

3. Task-Time Distributions

The task-time distribution for undersea facilities construction operation is shown in Tables VI-17 and VI-18. The detailed task analysis for the undersea facilities construction operation is presented in Appendix A.

Table VI-17 shows the task-time distribution as postulated for MAN-IN-THE-SEA systems. The total MAN-IN-THE-SEA operation time is estimated to be 50 days. Table VI-18 shows the task-time distributions as postulated for alternatives to MAN-IN-THE-SEA systems. The total alternative system operation time is estimated to be 60 days.

Table VI-17

TASK-TIME DISTRIBUTION FOR UNDERSEA FACILITIES CONSTRUCTION OPERATION: MAN-IN-THE-SEA SYSTEMS

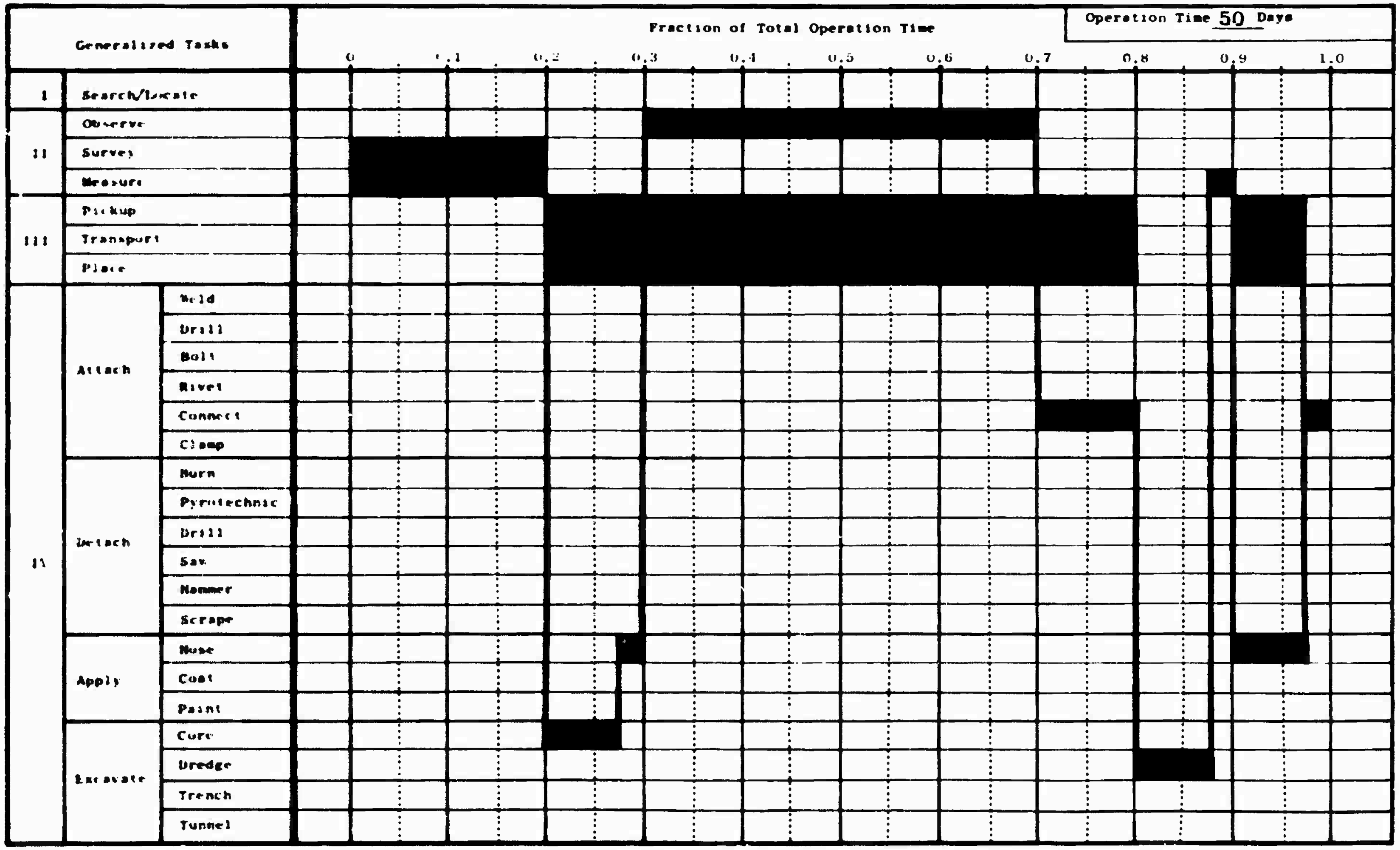
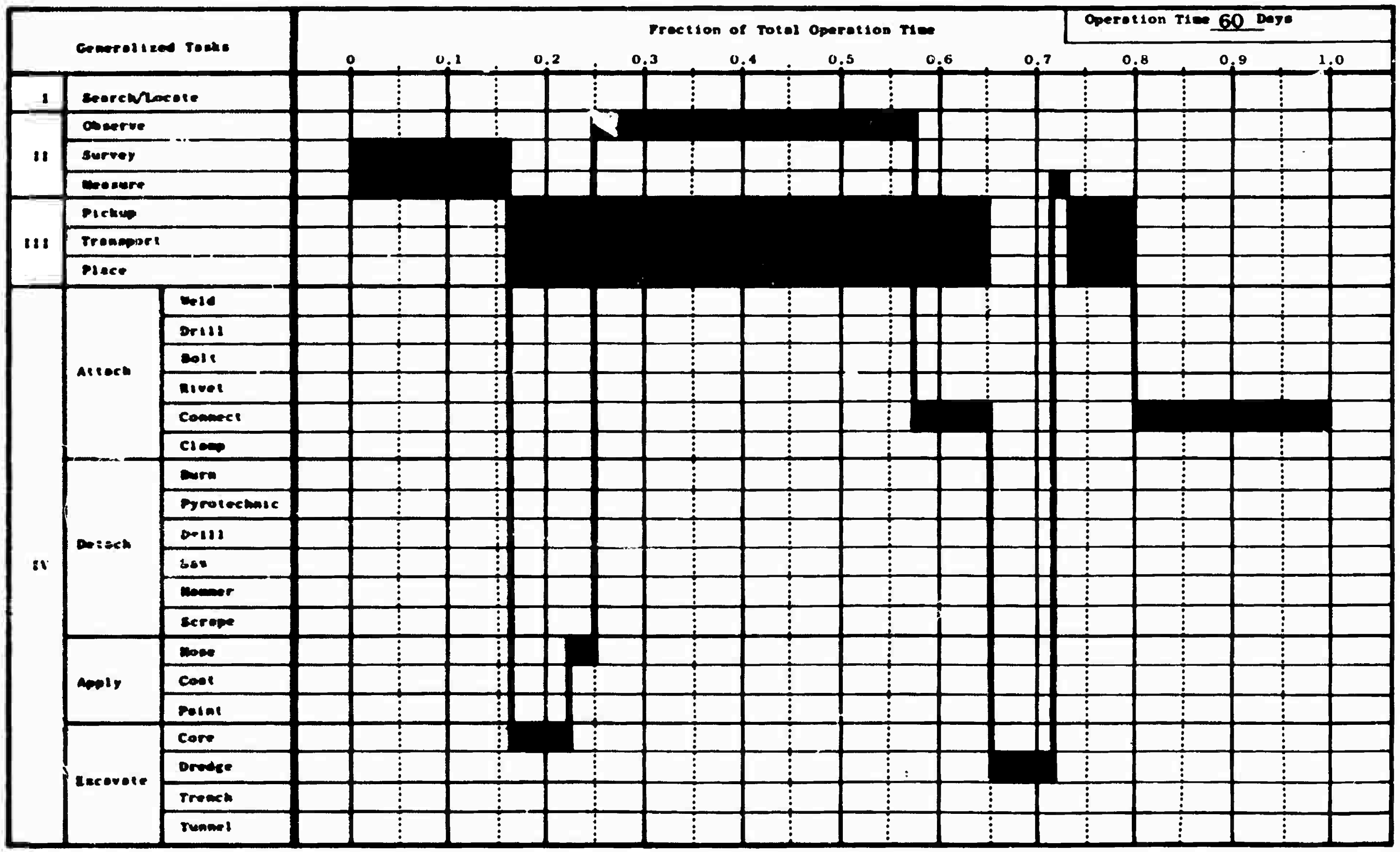


Table VI-18

TASK-TIME DISTRIBUTION FOR UNDERSEA FACILITIES CONSTRUCTION OPERATION: ALTERNATIVE SYSTEMS



4. Undersea Facilities Construction Operation Cost Comparison Summary

Work system investment costs for undersea facilities construction operation is the same as that shown for the ship salvage operation. This investment cost comparison is shown in Figs. VI-10 and VI-11. The following is the summary of investment costs comparison results:

- The dominant investment costs of work systems for undersea facilities construction operations are for the surface support vessel.
- For operating depths up to 150 ft MAN-IN-THE-SEA systems have definite investment cost advantages over alternative work systems. This advantage holds for the case where support vessel costs are not included and the case where support vessel costs are included.
- For depths up to 300 ft the ARTICULATED DIVING DRESS has investment cost advantage.
- For depths beyond 300 ft MAN-IN-THE-SEA systems have comparable investment costs to alternatives where support vessel costs are included and are not included. The exception is the case where the surface support vessel is not included for manned tethered vehicle. In this instance, the vehicle has the cost advantage.

The comparison of work systems operating costs for undersea facilities construction operation is shown in Figs. VI-16 and VI-17. The following is the operating costs comparison summary:

- For operating depths up to 150 ft MAN-IN-THE-SEA systems have a cost advantage over the alternative systems. This advantage is true for both cases where support vessel costs are and are not included.
- In the depth regime of 150-300 ft MAN-IN-THE-SEA and ARTICULATED DIVING DRESS have comparable operating costs.
- For operating depths exceeding 300 ft PTC,plus habitat MAN-IN-THE-SEA systems, have comparable operating costs to the alternative systems. The mobile habitat and PTC

augmented MAN-IN-THE-SEA systems have an operating cost advantage over the alternatives in both cases where support vessel costs are and are not included.

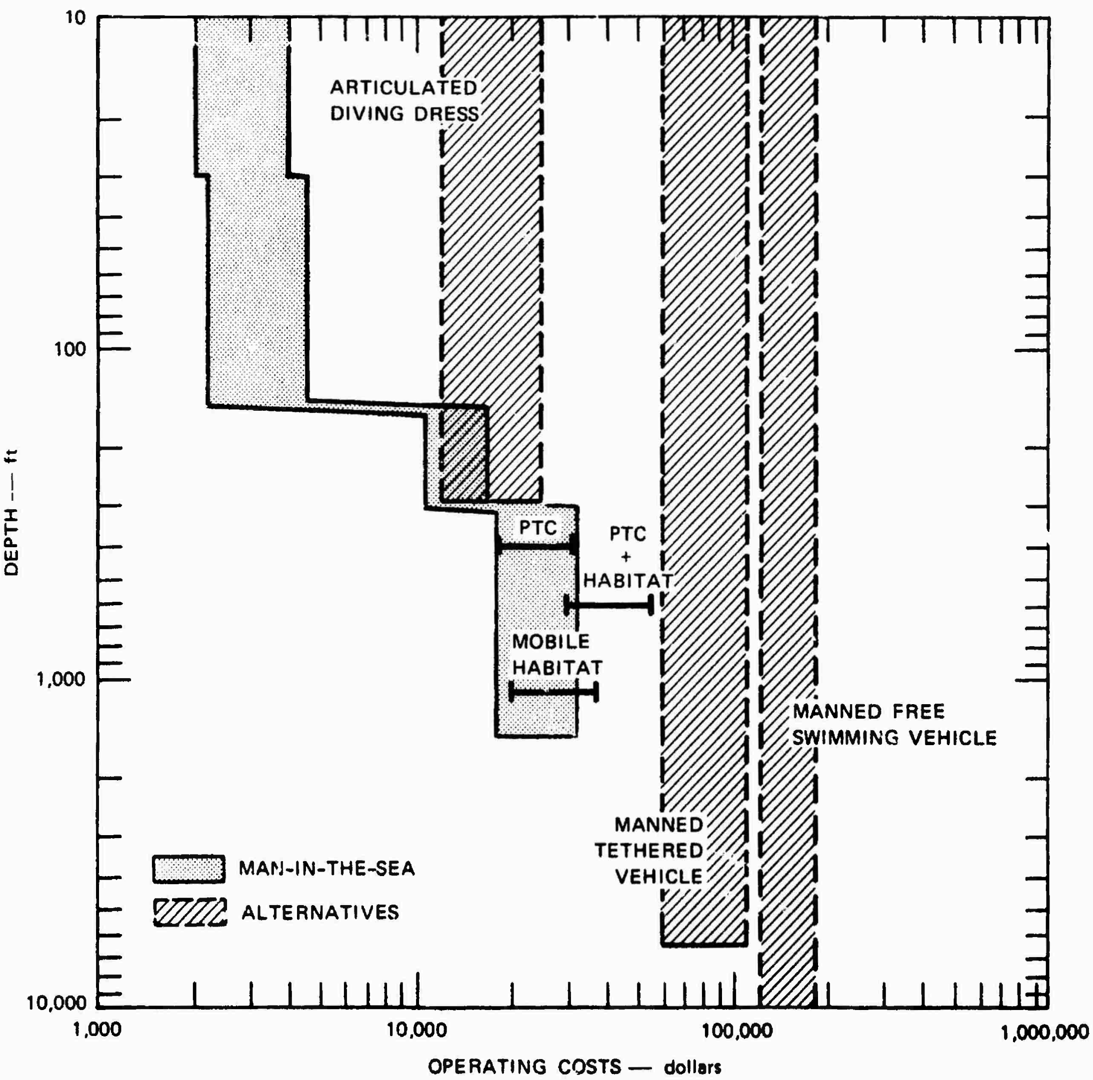


FIGURE VI-16 COMPARISON OF SYSTEMS OPERATING COSTS FOR UNDERSEA FACILITIES CONSTRUCTION (SUPPORT VESSEL COSTS NOT INCLUDED)

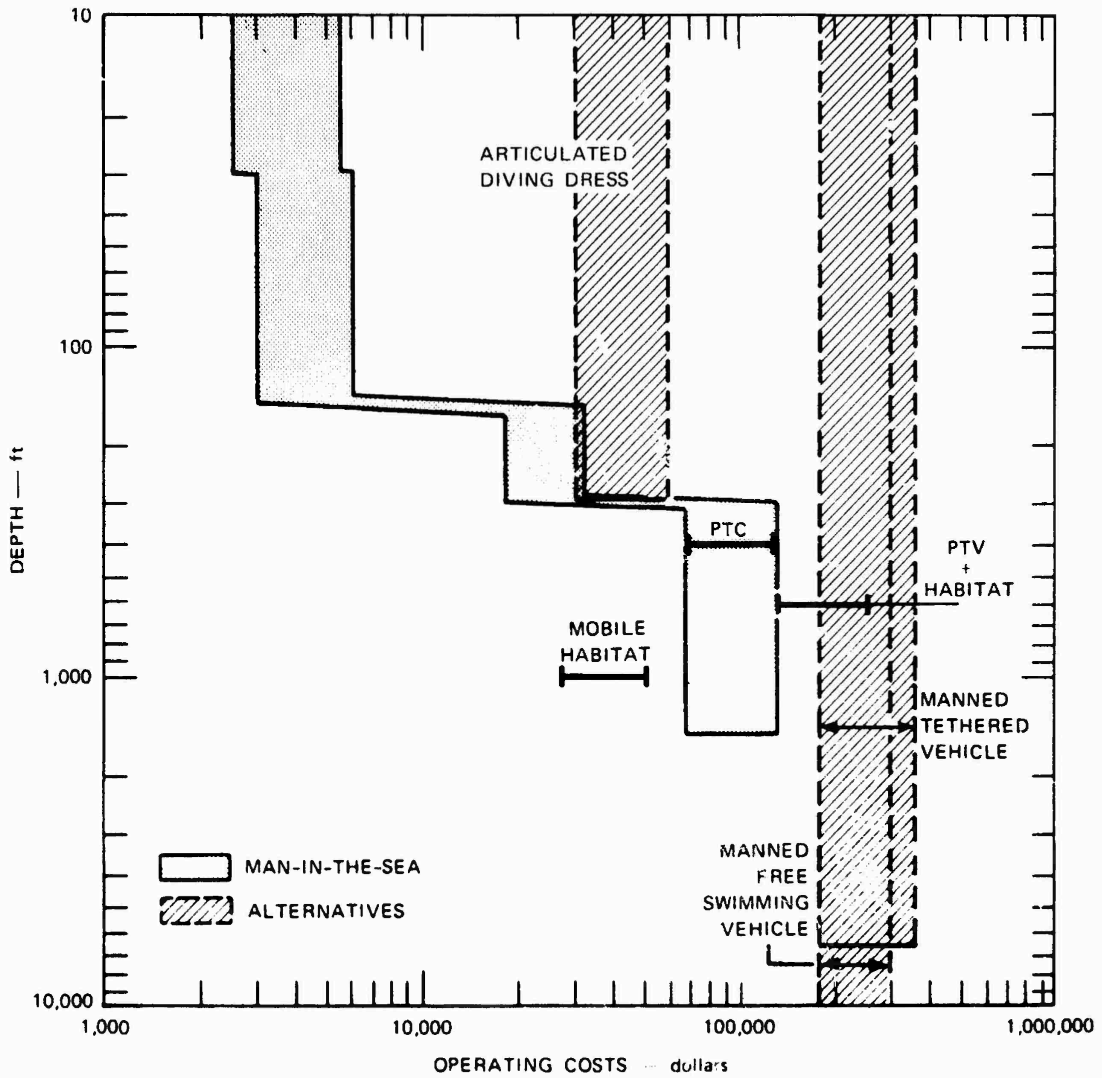


FIGURE VI-17 COMPARISON OF SYSTEMS OPERATING COSTS FOR UNDERSEA FACILITIES CONSTRUCTION (SUPPORT VESSEL COSTS INCLUDED)

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Appendix A

UNDERSEA TASKS ANALYSIS

CONTENTS

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CONTENTS (Concluded)

ILLUSTRATIONS

TABLES

Appendix A

UNDERSEA TASKS ANALYSIS

A. Analysis Method

The undersea tasks associated with the spectrum of Navy undersea missions or functional operations, in general, are similar in many of the undersea functional operations. This similarity is evident in the generalized task spectrum and its relation to the undersea functional operation. The generalized task spectrum comprises the following broad tasks: search/locate, observe/measure, survey, transport, emplace, attach, detach, apply, fill, and evacuate.

The oft-repeated descriptions of undersea naval functions in similar broad categories leave much to be desired from the point of assessing the required detail and time involved in the individual tasks. For a specific functional operation, however, viewing the particular task directly in the performance of a particular functional operation exposes the mechanical detail and time required that are difficult to assess in broader description.

Two functional operations were selected as focal points for the task analysis. These are the following:

- Salvage operations. The first is a description of the tasks involved in a relatively simple job of salvaging an aircraft. The second involves many more tasks than the first in that it is a description of salvaging a small ship.
- Construction operations. The first is a relatively simple problem--the construction of a permanent anchor. The second is more involved and describes the construction of an underwater facility.

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B. Task Analysis of Salvage Operations

The first, salvage or recovery, was selected because it is a real, current Navy requirement and will remain so in the near future. The second, undersea construction, is a projected requirement in which the Navy is developing capabilities to respond to construction requirements in deep water. These operations were selected to focus the task analysis on uncovering a spectrum of undersea tasks. In addition to the task analysis conducted for these functional operations, the project team reviewed a number of documents generated in the past that identify undersea tasks. This review, together with the results of the task analysis effort, provided a compendium of current and projected undersea tasks. Much of the MAN-IN-THE-SEA future support for naval requirements stems from the possible extension of operational depths of free swimmers/divers down to and beyond the continental shelf depths for possible future salvage requirements. The establishment of these future requirements appears to have been originated by the Deep Submergence System Review Group (DSSRG) report of 1 March 1964, which was concerned primarily with submarine rescue. Other salvage requirements are also established within GOR 46, Operational Support, and the related TSORs, SORs, and the ADO, although these documents were all initiated after 1 March 1964. In particular, SOR 46-16, Object Location and Small Object Recovery, and SOR 46-17, Large Object Salvage System (LOSS), are concerned with recovery of large objects, which are defined as having a deadweight of 1,000 tons or more. Included within the LOSS limits are submarines. Small objects are considered to be larger than a basketball and less than 10 tons.

With the advent of nuclear power and atomic warheads the salvaging of submarines and their missile warheads became much more significant than ever before, taking on worldwide political overtones. From a realistic point of view the loss of the military personnel and equipment and their "dollar" costs would appear to be subordinate to the primary need to salvage all equipment and weapons related to atomic energy. The world-wide alarm over the potential actuation of, or radiation from, any nuclear device in the ocean stems from the past record of the B-52 which crashed in Thule, Greenland, with an atomic weapon aboard, and a similar accident off Palomares, Spain. This type of salvage may not have an immediately obvious economic value other than the cost of producing the atomic weapon, but surely its intangible value is large when most of the world's governments are concerned when a U.S. military accident involves atomic weapons.

Salvage operations on a nuclear submarine could, and probably would, be carried out just to determine the cause of the sinking. This prospect is partly evidenced by the extensive search for any remaining structure to indicate why or how the THRESHER failure occurred.

Other immediate and very possible salvage requirements would be concerned with any naval ship sunk, particularly in a harbor or shallow water. Furthermore, aircraft, space hardware, and maritime shipping have definite salvage requirements. The costs of shipbuilding and re-outfitting versus the salvage costs would necessarily be a prime consideration in decisions related to salvage of naval ships, commercial maritime cargo carriers, and harbor barges. This type of salvage would probably have distinct economic values that could be easily assessed.

Aircraft salvage and space hardware, being much smaller and lighter, could have a higher probability of salvage success, but their tangible value is less significant than the intangible values, such as learning how well the space hardware did or did not function or what caused the aircraft failure. It is in this area of aircraft salvage that a large part of the current Navy salvage participation occurs. Almost 50% of the salvage operations conducted by the Navy during 1966, 1967, and most of 1968 were for aircraft belonging either to the Navy, Marine Corps, or the Air Force. A partial listing of recent and current salvage operations under cognizance of the Naval Salvage Office is provided in Table A-1. The operations listed are extracts from the more recent "hot sheets," which are filed chronologically in the Office of the Supervisor of Salvage, NSSC.

In the general salvage operations, there are basic, distinct salvage functions that must be performed. These functions are isolated and indicated in the diagram in Fig. A-1. Seven subfunctional tasks for the salvage operation have been indicated in the figure: (1) locate the wreck, (2) survey the position of the salvage on the bottom, (3) bring support equipment into the optimum position for support, (4) prepare and rig the salvage for lift, (5) break out the salvage if and when embedded in soft bottoms, (6) lift the salvage and tow to shallow water, and (7) position salvage for either wet or dry dock repairs.

Each of these subfunctional tasks, in turn, is further broken down to provide a more detailed description of the requirements entailed in each function. These breakdowns are shown in Figs. A-2 through A-4. As will be noted from the figures, not all subfunctions require a particular operation from below the surface, e.g., the subfunctions to locate salvage, position the salvage support systems, and position salvage for wet or dry dock repairs require no particular diver functional operation and are included only for completeness.

The initial search for the sunken object does not concern the diver directly. Because of his limited detection ranges relative to other search systems, he becomes involved in the operation only after the position of the object is precisely determined. The initial part of the total salvage operation is not outlined here. However, the THRESHER search, for example, indicates that underwater vehicles and surface search by dragging hooks, magnetic and acoustic devices,

Table A-1

RECENT AND CURRENT SALVAGE OPERATIONS UNDER THE COGNIZANCE OF THE NAVAL SALVAGE OFFICE

Salvage Object	Geographical Location	Depth, If Known (feet)	Date
F-4C	Gulf of Mexico		29 Mar '66
F-100	Coast of Florida		
Japan hulk	My Tho (RVN)*		25 May '66
F-8-E	Kaneohe Bay		2 Jun '66
USAF F-106	Lake Huron		15 Jun '66
MSO-493	San Juan	29	27 Jun '66
USAF C-130	Cape Vorella	300-500	6 Jul '66
SS TAESTUS (Italy)	Cape Hateras		11 Jul '66
50-ton barge	Harbor (RVN)		11 Jul '66
160 tons of ammo	Off a barge (RVN)		3 Aug '66
USAF F-84	Lake Michigan		18 Aug '66
USAF F-102	New Orleans		27 Sep '66
8-man helicopter	Gulf of Mexico		12 Oct '66
USAF F-105	Gulf of Mexico	60-100	15 Oct '66
SS GOLDEN STATE	Manila	Deep water	22 Oct '66
MSB-54	Nha Be (RVN)		31 Oct '66
USAF EC-121	Nantucket	180	12 Nov '66
F-8	San Diego		21 Nov '66
SS DANIEL J. MORRELL	Lake Huron	200	Dec '66
LST-912	Chu Lai (RVN)		4 Jan '67
MSB-45	RVN*		21 Jan '67
Dredge	RVN	20	1 Feb '67
HU-16E	Gulf of Mexico		6 Mar '67
USMC F-8-D	Kaneohe Bay		28 Feb '67
USAF F-102	Keohi Pt.		21 Mar '67
USN A-6-A Intruder	Cape Hatteras	40	5 Apr '67
USAF C-141	Cam Ranh Bay (RVN)		13 Apr '67
Super Connie	Nantucket		25 Apr '67

* Combat harbor clearance.

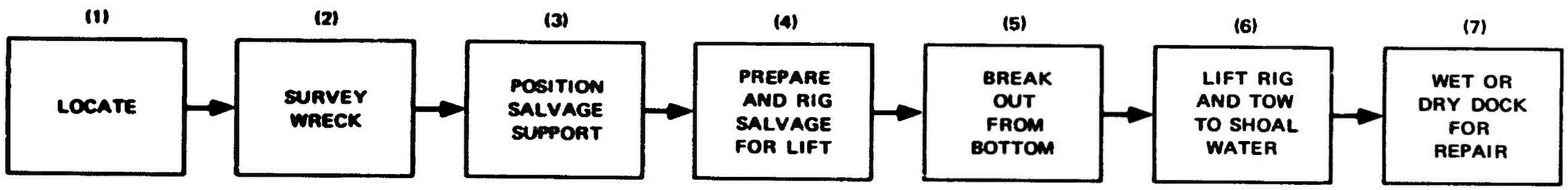

FIGURE A-1 OVERALL SALVAGE FUNCTIONS

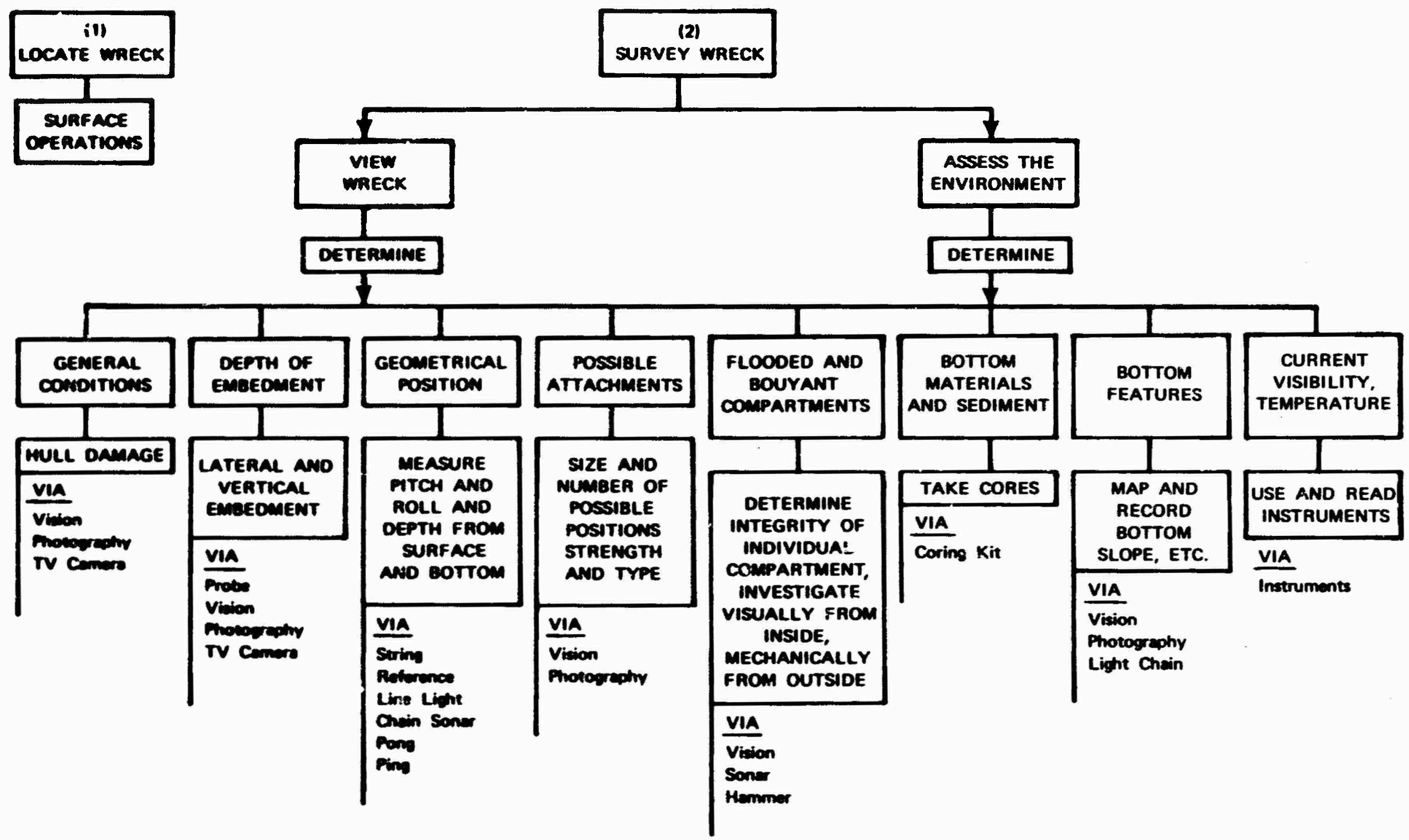

FIGURE A-2 LOCATE AND SURVEY WRECK FUNCTIONS

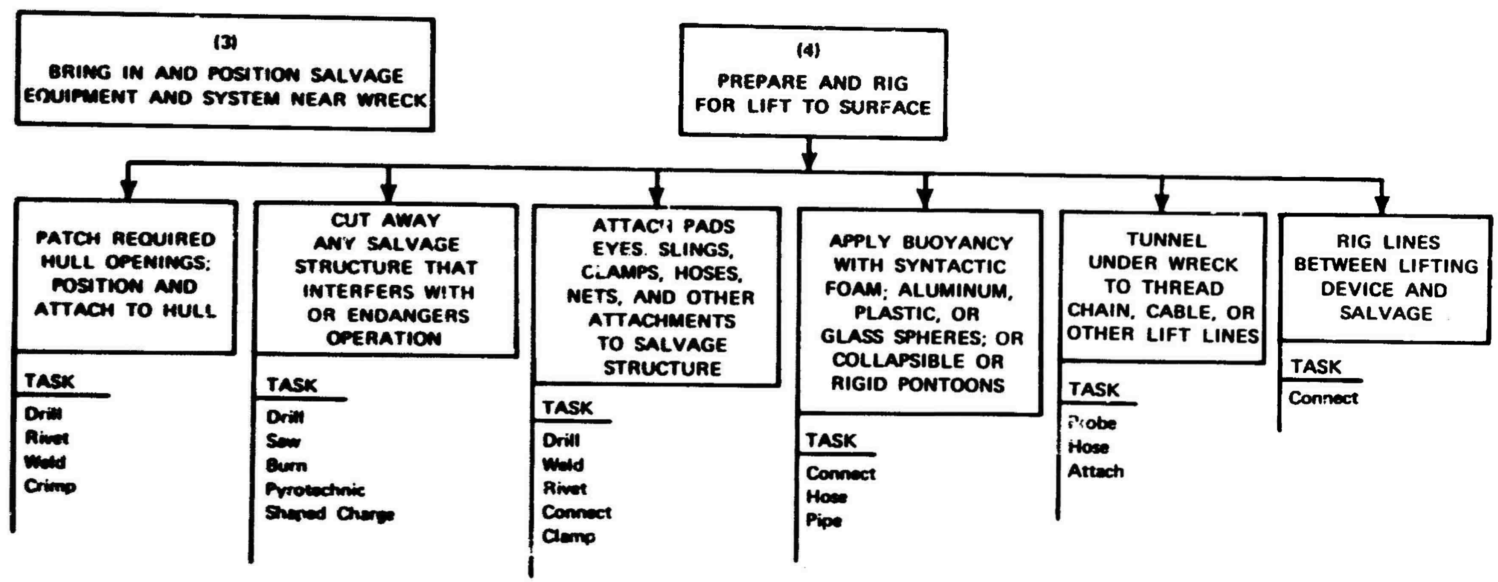

FIGURE A-3 POSITION SALVAGE EQUIPMENT AND RIG FOR LIFT FUNCTIONS

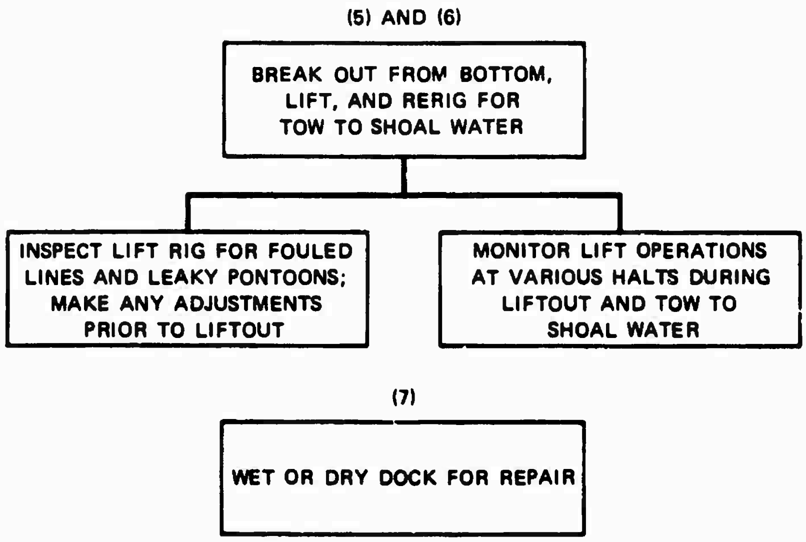

FIGURE A-4 BREAK OUT FROM BOTTOM AND LIFT FUNCTIONS

underwater photography, and television cameras will probably all prevail. Other salvage subfunctions, like position salvage support systems, will probably require only a few buoy plants and no divers. Also, towing and placing the salvage in port for dry dock repairs will not require divers except for checking the integrity of towing rigs.

Small Ship Salvage Task Outline

The ship salvage diagrams are described in the following detailed Small Ship Salvage Outline. Assuming the wreck has been located on the ocean bottom and the decision to salvage it has been made, the salvage job would proceed as outlined here.

1. Survey Wreck

The condition of the wreck must be determined. Determine general conditions and hull damage. Encircle wreck near enough to obtain required details for determining possible hull damage and depth of embedment. Obtain geometrical position relative to bottom, possible attachments, and flooded and buoyant compartments.

- Visual survey for first assessment
- Photography survey for permanent record
- TV camera survey for topside information.

Determine hull damage by using:

- Visual inspection
- Photography inspection of permanent record
- TV camera inspection for topside information.

20 hours

Determine depth of embedment by using:

- Steel probe to determine depth of sediment, clay bottom, or other hard bottom types with minimum sediment overlay. This is done at several places around the ship to determine both type of material and depth of embedment to determine the pullout forces.

4 hours

- Visual inspection of probe
- Photography probe for permanent record
- TV camera for visual inspection topside.

4 hours

Determine geometrical position, pitch, roll, and depth from surface and bottom by using:

- Reference line placed on bottom and buoyant lift for extending light chain
- Sonar to measure depths to ship bottom embedded in mud
- Sonar ping from corner reflectors set up for measuring distances.

6 hours

Determine possible attachment parts and possible strength and type of attachment by using:

- Visual inspection
- Photography inspection for permanent record.

Determine flooded and buoyant compartments and determine integrity of structure by:

- Visual inspection inside ship
- Visual and mechanical inspection outside ship
- Use of pneumatic hammer and ultrasonic sounding on outside of structure to locate buoyant compartments and water-filled volumes inside.

10 hours

2. Assess the Environment

Determine bottom material and sediment by using: — 2 hours

- Vane shear meter to determine shear strength indication of required lift of focus

- Hydraulic or pneumatic coring device to determine bottom materials. Possibly could use explosive device if necessary. — 8 hours

Determine bottom features by using: — 6 hours

- Vision
- Photography
- Light measuring chain and establish bench marks.

Determine current, usability, and temperature by using: — 3 hours

- Hand held calibrated instruments.

3. Prepare Salvage Plan

Compute breakout forces from sediment shear values and hull penetration. Bring in and position salvage equipment and system near wreck. Prepare and rig salvage for lift to surface. — 2 weeks

Cut away any salvage structure that interferes and endangers operation by using: — 4 hours

- Pneumatic and hydraulic impulse drill, saw, pyrotechnique and shaped charges
- (Use of power velocity tools will improve in time.)

Patch required hull openings with prefabricated sheet steel using:

- Pneumatic and hydraulic drill or power velocity tools
- Power velocity and stud bolts and attach with nuts
- Welding equipment to weld plates for metal bond.

8 hours/ patch

4. Technique I

Prepare to lift with attached cable sling around salvage fore and aft.

Use hydraulic hose to dig cable trench under salvage, two trenches in soft sediments, good current to carry away debris.

- Accept hydraulic hose from surface
- Emplace one-man anchor for reactive force from hydraulic nozzle or use reactive nozzle if available to remove mud and bottom sediments in trenching under salvage
- Receive cable from surface
- Thread cable lead (reeving line) through trench under salvage
- Pull cable through under salvage and attach to surface cable by laying loops over snap hook.

24 hours

5. Reduce Lifting Load

To reduce lifting loads in cable and on surface lift equipment apply buoyancy with syntatic foam or aluminum and glass spheres.

- Accept hose from topside to apply syntatic foam
- Attach hose receptable by drilling holes and using bolts and nuts to attach a prefab and hose receptacle
- Drill holes and bolt patches to salvage over any openings to contain pumped foam
- Apply foam from topside while diver is topside and away from possible danger from buoyant rise.

17 hours

6. Rig Pontoons and Lift Lines

- Bring neutrally buoyant pontoons and cable attachment into work area
- Attach cables and lift lines to pontoons prior to lift
- Attach pneumatic hose to pontoons prior to lift
- Attach lift cables from surface vessel to lift sling prior to lift using bolts and nuts.

10 hours

7. Increase Pontoon Buoyancy

Increase lift force to break out wreck from bottom.

Aircraft Salvage Task Outline

1. Establish Salvage Plan and Surface Operations

2. Inspect General Condition of Salvage on Ocean Bottom — 4 hours

   - Conduct preliminary visual observation
   - Use underwater camera for permanent record
   - Use TV camera and record topside.

3. Prepare to Lift--Plan Lift Procedure — 5 hours

If commercial aircraft is to be salvaged, find and remove flight recorder first.

- Enter flight compartment of aircraft for flight recorder
- Use impulse wrench and hammer to remove nuts and bolts holding recorder to structure
- Use saw to cut any bolts that cannot be removed
- Cut all electrical leads with knife, shears, etc.
- Lift flight recorder out of flight compartment. If military air craft is salvage job, remove IFF.
- Enter flight compartment or aft radio section
- Position explosive for destruct after sawing, punching, or drilling access to IFF equipment.

4. Lift Aircraft to Surface

Plan is to attach cable sling around fuselage, fore and aft. Use hydraulic hose to dig cable trench under fuselage. Two trenches are dug in soft sediment. Area is where good bottom currents will carry away debris.

Technique I

Prepare to lift fuselage with cables attached from surface vessel.

- Accept hydraulic hose from surface
- Set an anchor to work against the reactive force from hydraulic fluid nozzle or use reactive nozzle if available.
- Receive cable from surface
- Thread cable lead (reeving line) through trench under fuselage
- Pull cable through under fuselage and attach to buoy
- Attach cable to surface cable by laying loops over snaphook or a sophisticated rigging hook
- Bolt lift-sling to surface-lift cable snaphook for security.

— 5 hours

Technique II

Prepare to lift fuselage with a buoyant force at aircraft for lift requirements. Use "Foam in Salvage" (FIS) technique.

- Conduct preliminary visual observation
- Use underwater camera for permanent record
- Use TV camera and record topside

— 4 hours

- Enter flight compartment of aircraft for flight recorder
- Use impulse wrench and hammer to remove nuts and bolts holding recorder to structure
- Use saw to cut any bolts that cannot be removed
- Cut all electrical leads with knife, shears, etc.
- Lift flight recorder out of flight compartment (if military aircraft is salvage job, remove IFF)
- Enter flight compartment or aft radio section
- Position explosives for destruct after sawing, punching, or drilling access to IFF equipment.

— 5 hours

- Accept hose from topside to expel gasoline from wing tank and fill with syntatic foam
- Use impulse punch tool to release fuel from wing tanks
- Attach hose receptable by drilling holes and use bolts and nuts to attach a prefab plate and hose receptable
- Accept hose from topside at fuselage for placing foam inside fuselage
- Drill holes and bolt patches to fuselage over any openings to contain plastic foam
- Apply foam, keeping distance away from possible danger from buoyant rise--fuselage, four wing tanks
- Complete attachments to salvage for towing near surface when aircraft is floating.

7 hours

C. Task Analysis of Undersea Construction

Undersea construction as interpreted here is divided into two basic and separate functions: (1) attaching foundations rigidly, firmly, and permanently into the ocean bottom for the planned undersea facility; and (2) attaching and assembling prefabricated components forming the undersea facility that is attached to the foundation. This is not an oversimplification, but rather a concise separation and definition of the two major aspects of undersea construction, which is shown in a general diagram, Fig. A-5.

Although undersea construction appears to be an extension of on land construction practices into the sea, due to restrictions enforced by the underwater environment and sea floor, many land construction practices will not be applicable. The same soil properties such as shear strength, compressive strength, and cohesion strength are basic for determining the bearing loads which can be supported under particular conditions both on land and on the ocean bottom. However, undersea foundation investigation also requires an estimate of possible mud slide, rock slides, turbidity currents, and general area instability.

After the overall site survey is completed, a particular area is localized and the best place to establish the facility is determined. This involves coring, in situ strength tests, bottom and subbottom profile surveys, detailed topography surveys, and microrelief surveys by actual inspection, either visual, camera, or TV.

With a detailed construction plan formulated and work ready to begin, bottom stabilization, if necessary to reduce or eliminate turbidity problems, is carried out and the actual construction is begun. This requires drilling, excavating, earth moving, lifting, transporting, and finally, assembly.

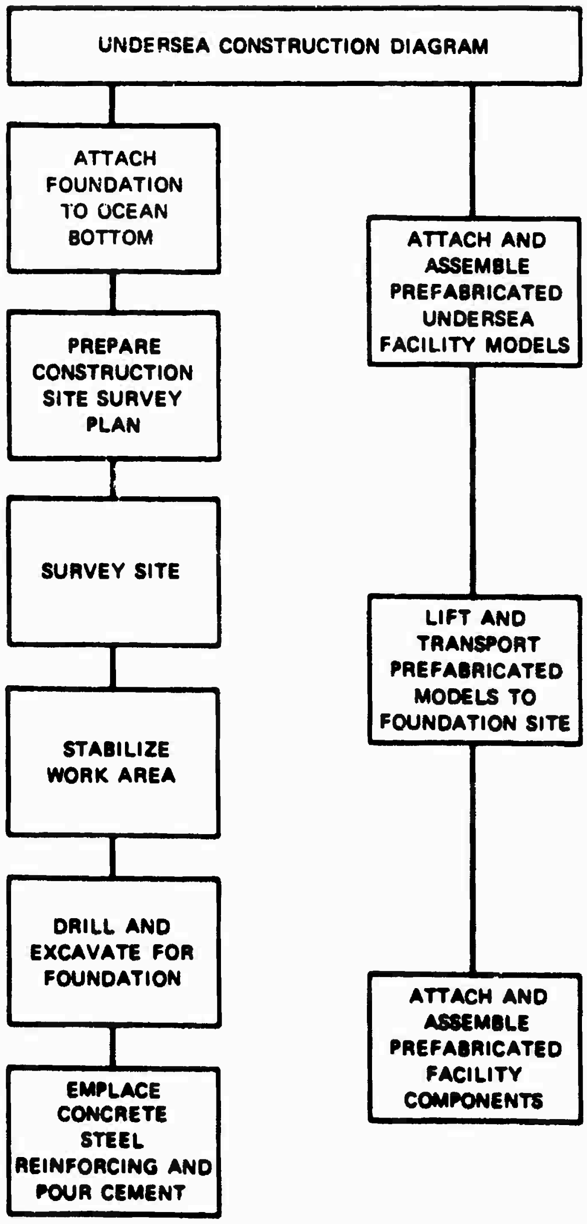

FIGURE A-5 UNDERSEA CONSTRUCTION OPERATION SUMMARY

Requirements for two examples of construction work--a relatively simple example first and then a more complex example--are broken down into detail. These are the emplacement of a rigid, permanent undersea anchor and the construction and assembly of an undersea facility.

Two descriptions that provide the detailed tasks involved for both construction jobs are provided. A detailed outline of the required tasks for the relatively simple undersea construction example (the emplacement of a simple, rigid, permanent underwater anchor) is given first. Included are the estimated times for each task. A second description is a task outline to perform a more complex undersea construction job, the construction and assembly of an undersea facility. The facility under construction could be any facility that requires a rigid, permanent connection to consolidated sedimentary rock below the bottom sediments.

Although greater detail for each subtask would be desirable for a more accurate assessment per task, this can come only from experimental data that are not yet available. Included also are estimated times. These times are not critical unless the values assigned here are grossly inaccurate.

Undersea Naval Facility Task Outline

1. Prepare Construction Site Plan and Plan Survey

2. Prepare to Obtain Bottom Conditions, Soil Stability, Bearing Strength, Sediments, Overburden, Semi-consolidated Rocks, and/or Rock Depths

   - Use held vane shear probe over large area — 10 hours
   - Use preliminary gravity coring device, guiding coring device lowered from topside into position — 30 hours
   - Use subbottom sounding sonar to determine layering depths
   - Perform in situ plate bearing test on sediments by emplacement of plates and observance of leveling rod — 10 hours
   - Remove buoyancy floats from bearing plates (maybe five) and observe sight-leveling rod to determine vertical deflection with each increase in applied load — 10 hours
   - Guide bottom-sitting, deep coring device (200 ft) lowered from topside (repeat); manipulate hydraulic drive from bottom — 40 hours
   - Read instruments for measuring turbidity, current velocity, etc. — 1 hour/day
   - Survey area with light chain and leveling device; use buoyant device below surface and attach sonar pinger to measure bottom slope; operate pinger at underwater float platform; establish four points for piling support; drill points. — 20 hours

3. Plan to Place Four Cement, Steel Reinforced Concrete Piles 60 ft Below Ocean Bottom Into Sedimentary Rock (must penetrate 50 ft of mud sediment before reaching consolidated sedimentary rock, then drill 10 ft into sedimentary rock)

4. Stabilize the Work Area to Reduce Turbidity — 6 hours

- Cover work area with nylon mattress prior to concrete overlay
- Accept flexible hose from topside and fill mattress section with concrete, forming thin concrete layer for on-bottom work, reducing turbidity problems.

5. Drill Piling Holes from Topside — 160 hours

- Guide power drill hydraulic head to bottom location where 50-ft deep, 4-ft-diameter hole is drilled in sediment--four holes; hydraulic power from topside; adjustment and operation from bottom.

6. Prepare for Blasting Out 4-ft-Diameter Hole, 10 ft Deep, Into Sedimentary Rock — 44 hours

- Guide drill pipe from topside to drill explosive charge hole 10 ft deep--four holes
- Set explosive charges in all four holes.

7. After Blasting, Remove Rubble from Hole — 16 hours

- Accept and guide hydraulic or pneumatic pumping tube operating from topside for removing rubble in hole--four holes; do not enter hole.

8. After All Holes Are Cleared of Fractured Debris — 4 hours

- Reinsert drill or comparable measuring device to determine hole clearance--guide work from topside--four holes.

9. <u>Prepare to Insert Steel Concrete Reinforcing Beam, 80 ft Long, Into Each of Four Separate Holes</u> — 20 hours

- Accept beam held at topside and guide into hole
- Accept flexible concrete hose or tremie pipe held at topside
- Divert cement into 50-ft by 4-ft-diameter hole, which contains reinforcing beam held by topside; do four holes.

10. <u>After Steel Reinforced Concrete Piers have Cured, Attach Cross Beams, Making a Rectangular Platform to Attach and Assemble the Planned Facility</u> — 16 hours

- Position cross beams, which are cabled and supported to pontoons to provide neutral buoyancy; pontoon air control is provided from topside
- Attach beams with bolt and nuts through prefabricated holes in both supporting pier beams and cross support beams.

Simple Rigid, Permanent, Undersea Anchor Task Outline

The planned construction is to drill a 50-ft by 4-ft-diameter hole through 40 ft of sediment and 10 ft of consolidated rock and fill with steel reinforced concrete to provide am immobile anchor.

1. Prepare to Obtain Bottom Conditions, Soil Stability, Bearing Strength, Sediments, Overburden, and Depth to Semiconsolidated Rock, and/or Rock Bottom

    - Use vane shear probe over large area
    - Use preliminary gravity coring device, guiding coring device lowered from topside into position
    - Guide bottom setting deep coring device (200 ft) lowered from topside (repeat); manipulate hydraulic drive from bottom
    - Perform in situ plate bearing test on sediments by emplacement of plates and observance of leveling rod
    - Use subbottom sounding sonar to determine depth of first layer.

    — 40 hours

2. Drill Single Hole From Topside

    - Guide power drill hydraulic head to bottom location where 50-ft-deep, 4-ft-diameter hole is drilled in sediment; hydraulic power from topside; adjustment and operation from bottom.

3. Prepare for Blasting Out 4-ft-Diameter Hole, 10 ft Deep, Into Sedimentary Rock

   - Guide drill pipe from topside to drill explosive charge hole 10 ft deep
   - Set explosive charges in hole.

   10 hours

4. After Blasting, Remove Rubble From Hole

   - Accept and guide hydraulic or pneumatic pumping tube operating from topside for removing rubble in hole; do not enter hole.

   4 hours

5. Prepare to Insert Steel Concrete Reinforcing Beam 80 ft Long, Into Cleaned Out Hole

   - Accept beam held at topside and guide into hole
   - Accept flexible concrete hose or tremie pipe held at topside
   - Divert cement into 50-ft by 4-ft-diameter hole, which contains reinforcing beam held by topside.

   5 hours

6. After Steel Reinforced Concrete Piers Have Cured, Attach Prefabricated Anchorage Attachment, Buoy Chain, and Buoy to Steel Beam

   2 hours

Appendix B

MAN-IN-THE-SEA SYSTEMS

CONTENTS

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CONTENTS (Concluded)

ILLUSTRATIONS

TABLE

Appendix B

MAN-IN-THE-SEA SYSTEMS

A. General

The growing interest in and concern with the exploration of the oceans and the exploitation of ocean resources have resulted in the evolution of a spectrum of systems for accomplishing undersea tasks. These undersea work systems are separated into two distinct classes in terms of how man is utilized. The first system class employs techniques that place man in the ambient ocean pressure environment and enable him to achieve direct contact with his working environment. These ambient pressure systems, referred to as "MAN-IN-THE-SEA" or "Wet" systems, are the focal point of this study. The second system class employs techniques that enable man to conduct undersea operations in a normal atmospheric environment. The atmospheric environment is provided through the use of a protective pressure vessel or through location of a man on the ocean surface who operates a remote controlled device. The atmospheric pressure systems, referred to as the "Dry" or "Hard" systems, are alternative techniques in accomplishing underwater work whereby man is not exposed to the hazards of ambient pressure environment.

The various options within the MAN-IN-THE-SEA work systems categories are described in this appendix. A brief review of historical developments and current research and development focus, together with a projection of 1975-85 work system configurations, are provided.

B. Historical Developments

The term MAN-IN-THE-SEA is used in this study to define any undersea system that requires exposing man to the ambient ocean pressure. MAN-IN-THE-SEA systems therefore encompass all those techniques associated with the diving technologies.

Man's progress toward reaching greater diving depths and duration is a result of overcoming both physiological and technological problems. Until the 19th century diving depth limits were imposed by such technological constraints as diving helmets, diving bells, and air compressor design. As the technological problems were solved, divers went deeper and remained longer, and the physiological problem of decompression was encountered. Decompression sickness or "the bends," one of the hazards of diving, was diagnosed in the 1870s. Under pressure the inert gas in a breathing mixture (nitrogen in air) diffuses into the blood and other tissues. If the pressure is relieved too quickly, as in a rapid ascent from working depth, bubbles form in the tissues, much as they do in a bottle of carbonated water when it is opened. Sudden decompression from a long, deep dive can be fatal; even a slight miscalculation of decompression requirements can cause serious injury to the joints or the central nervous system. A diver must therefore be decompressed slowly, according to a careful schedule. Slow decompression enables diffusion of the inert gas from tissues to the blood and from the blood out to the lungs. Whereas decompression sickness was diagnosed and a cure (slow decompression) was developed, other physiological problems were encountered. These problems are nitrogen narcosis (inert gas toxicity) and oxygen poisoning (oxygen toxicity).

In an effort to solve the nitrogen narcosis problem the Navy and the Bureau of Mines in 1924 began to conduct joint experiments with breathing mixtures consisting of inert helium gas and oxygen. By 1927 the work had progressed to the point where human subjects could be used. In 1937, using a helium-oxygen gas mixture, two Navy divers reached a simulated depth of 500 ft in one of the tanks at the Navy's Experimental Diving Unit.

These dry land experiments were put to operational use in May of 1939 when the U.S. submarine SQUALUS sank in 243 ft of water. The helium-oxygen diving technique was used in 640 dives to the submarine without death or serious injury. On the basis of data obtained during the SQUALUS dives, the U.S. Navy established 380 ft as the new limit for operational diving, with a time limit of 30 minutes on the bottom.

Up to that time the hard hat technique was used, that is, man was tethered to a surface air compressor or gas supply. This tether drastically constrained the mobility of the diver. In the 1940s, the technological development commonly known as SCUBA or self-contained underwater breathing apparatus allowed new freedom for man working in the underwater environment. Divorced of the need for the constraining umbilical to the surface, man was able to move about in the ocean with relative freedom. However, with the SCUBA technique, his depth-time capability is still limited by the amount of gas he is able to carry on his back.

The principal limitation in depth and duration of dives up to the late 1950s was still the requirement for decompression. The limit for U.S. navy operation dives remained 380 ft for 30 minutes on the bottom. Without complications, a dive of this depth and duration requires more than three hours of decompression--an unfavorable ratio of working time to decompression time of 1 to 6. This unfavorable ratio of work-to-decompression time was solved by the development of the "saturated diving" technique. Saturated diving technique capitalizes on the fact that at a given depth the amount of inert gas dissolvable into the body tissue is limited. After about 24 hours at a given depth the tissues become essentially saturated with inert gas at a pressure equivalent to the depth; they do not take up significantly more gas no matter how long the diver stays at that level. For example, a diver saturated to 300 ft requires the same decompression time (approximately 2-1/2 days) whether he spends 1 day or 1 month at depth. Therefore, if a diver must descend to a certain depth to accomplish a time-consuming underwater task, it is far more efficient for him to stay at that depth than to return to atmospheric conditions (surface) repeatedly, spending hours in decompression each time.

The U.S. Navy's MAN-IN-THE-SEA Program is based on the development of the saturated diving technique. The first experiments in the field of saturation diving were begun by the U.S. Navy in 1957 under the direction of Captain George Bond, using first a standard decompression chamber and then the climate-altitude chamber installed at the Naval Medical Research Laboratory in New London, Connecticut. These experiments were given the code name Genesis I, and the first phases were concerned with the reaction of animals under long term exposure to pressure and synthetic gas mixes. Late in 1962 three men were exposed to a helium-oxygen breathing mixture at sea level pressure for 6 days. There were no observable physiological or psychological changes in the subjects.

In the next phase of Genesis I, conducted early in 1963, three Navy men lived for 7 days in a two-section pressure chamber at the Experimental Diving Unit. The pressure in the chambers was similar to that encountered at a depth of 100 ft. The final phase of Genesis I was conducted at the Naval Medical Research Laboratory Test Chamber, with three men spending 12 days at a simulated ocean depth of 200 ft, again breathing a helium-oxygen gas mixture. The Genesis I experiments were completely successful and provided the physiological base for subsequent SEALAB experiments.

Since Captain George Bond's original proposal for the saturated diving technique, both the American inventor, Edwin Link, and the French oceanographer, Jacques-Yves Cousteau, have conducted significant work to advance saturated diving techniques. Their experiments were designated "MAN-IN-SEA" and "CONSHELF," respectively.

In the summer of 1964 the U.S. Navy conducted its first in situ experiment, designated SEALAB I, near the Oceanographic Research Tower, Augus Island, off Bermuda. Men lived in a 40-ft-long chamber at a depth of 193 ft for 11 days. An extensive program of physiological studies was successfully pursued.

In the fall of 1965 the U.S. Navy conducted the SEALAB II experiment at La Jolla, California. Three 10-man teams remained at a depth of 205 ft for 15 days each. One man remained at that depth for the full 45 days of the experiment. In addition to living underwater and conducting a multitude of physiological experiments, underwater work tasks in simulated salvage. oceanography, and construction were performed. In all, the three teams achieved more than 300 man-hours of work outside the habitat.

In the spring of 1969 the U.S. Navy, Department of the Interior, the National Aeronautics and Space Administration, the General Electric Company (with assistance from the Coast Guard), the University of Pennsylvania, and other government, industry, and academic organizations conducted the cooperative program named Tektite I. This program placed four marine scientists at a depth of 50 ft for 60 continuous days.

A summary of saturated diving or prolonged undersea living experiments conducted in the U.S. Navy MAN-IN-THE-SEA Program is shown in Fig. II-1. (See Section II of this report.) Civilian experiments by Edwin Link, Jacques-Yves Cousteau, and the work of the Westinghouse-Marine Contractor consortium are also summarized in the figure.

The clearly defined needs of the U.S. Navy for salvage and submarine rescue, and the commercial needs of off-shore oil recovery operations and salvage operation gave impetus to the transformation of the saturation diving technique from experimental to operational systems. Except in isolated cases, fully saturated long term undersea habitation and work have not been fully exploited. The principal reason has been that such operations have not been required. Notable exceptions have been the repair of the Smith Mountain Dam and the off-shore oil rig salvage operation in the Gulf of Mexico. These operations, which were conducted by the Westinghouse-Marine Contractor consortium, were not true undersea habitation operations since the men were delivered to the work site at about 200 ft by a transfer capsule pressurized to the working pressure. After the work period the men returned to the surface in the transfer capsule and there entered a chamber that was also pressurized to the pressure at the working depth. In this system the men lived in the ambient pressure environment for up to a week, alternating between work site and rest cycle in the surface chamber.

C. Research and Development Focus

To satisfy the goals of prolonged habitation and accomplishment of useful work by man at ocean depths, on-going research efforts are seeking a better understanding of the physiological and psychological problems related to exposing man to the ambient environment. Major R&D efforts are also being directed toward advancing the technology associated with supporting the unshielded man. The psychological aspects of MAN-IN-THE-SEA research are focused toward the understanding and measurement of diver performance impairment resulting from ambient environment exposure. MAN-IN-THE-SEA performance capabilities are reviewed later in this appendix in terms of: (1) psychomotor performance, (2) mental task performance, (3) sensation and perception, and (4) communications. Current physiological research efforts are directed toward such problem areas as decompression, oxygen toxicity, inert gas toxicity, pulmonary ventilation, and hydrostatic force effects. Technological R&D efforts, which are closely integrated with physiological research, are concerned with breathing gas analysis, long duration breathing gas supply systems, heated diver dress, and diver functional support elements, including tools, communication and navigation equipment, and extended sensory aids. The following discussion examines the focus of R&D efforts associated with the physiological and technological aspects of MAN-IN-THE-SEA concepts.

1. Physiological Research

a. Decompression

Decompression is the most familiar problem related to diving operations. This problem results directly from the increased solubility of gases with increased pressure. Exposure to high hydrostatic pressures during a dive causes components of the breathing gas to be taken up in solution by all body tissues. The rate of return to the surface is absolutely limited by the rate at which excess dissolved gases in the tissues can be eliminated. The rate of gas uptake or elimination is directly proportional to the diffusivity and gas partial-pressure gradient at the tissue-blood and lung-blood interfaces. Reliable decompression tables (safe ascent rate) for extended depth-time dives are being developed through improved computation methods and experimental validation. It is estimated by diving physiologists that, regardless of the inert gas used in a breathing mixture, the rate of ascent following prolonged submergence will never be increased much beyond the 10 minutes per foot now achieved. This means that normal unaided decompression following a saturation dive to 500 ft will continue to require about 3-1/2 days. Inert gas elimination by unaided decompression will remain the primary factor limiting diving efficiency, i.e., useful diving time per unit of total time invested.

Several techniques are being examined that may provide practical aids to speed up decompression or to improve the safety of divers. These aids include: (1) the use of high oxygen tension, (2) the use of methods for extending oxygen tolerance, (3) the use of multiple gas mixtures, (4) the alternation of inert gases in the breathing mixture, (5) the combining of alternation of inert gases with fluctuation of oxygen tension, and (6) the use of drugs to accelerate blood flow. A very advanced technique that cannot be classed as an aid to decompression is the concept of fluid breathing. This technique is an attempt to circumvent the whole problem of decompression by eliminating the need for inert gas. The following is a summary of the techniques being studied as aids to speeding up decompression.

(1) High Oxygen Tension. The use of high oxygen tension is probably the first decompression aid discovered (1935) and will probably continue to be the most useful technique to speed up decompression. The technique calls for the use of a high concentration of oxygen in the breathing mixture. The physiological principles exploited by this technique are to minimize the inert gas diffusion gradient (partial pressure difference) in the lung-blood and tissue-blood interfaces during descent and to maximize the diffusion gradient during ascent. The extent that the high oxygen tension technique can be used to aid decompression is limited by adequate definition of human oxygen tolerance. The problems encountered with oxygen at high pressures, i.e., oxygen toxicity, are discussed below.

(2) Interrupted Exposure to High Oxygen Tension. A use of interrupted exposure to high oxygen tension is an attempt to circumvent the oxygen tolerance limits. It has been found that animals exposed

intermittently to high oxygen tensions can tolerate longer, total high oxygen tension exposure time. This approach is being used in a limited way to treat divers suffering from decompression sickness (bends).

(3) Multiple Inert Gas. The use of multiple inert gas in breathing mixtures to aid decompression has been considered for several decades. The basic concept is clear, but results from actual trials are not conclusive. The fundamental assumption is that each gas in a gas mixture or dissolved in body fluids behaves as though it were the only gas present. The principle is that individual inert gas partial pressure will be decreased proportionately with the increased number of inert gases used. Thus, the diffusion gradient for each gas is reduced. A hypothetical gas mixture offered in the First Symposium on Underwater Physiology uses nine gases, including oxygen, nitrogen, hydrogen, helium, neon, argon, krypton, xenon, and radon. The use at nine atmospheres of pressure with a nine-gas mixture (equal volume) should not result in excess saturation of tissue fluids because each gas in the mixture is at a maximum partial pressure of 1 atmosphere. Nevertheless, severe decompression sickness does occur after exposure to multiple gas mixtures. The explanation for the effect is that, once a cavity or a small bubble is formed, its growth depends upon the sum of the partial pressures of all gases in the tissue.

(4) Alternation of Inert Gases and Fluctuation of High Oxygen Tension. A logical extension of the multiple gas breathing mixture technique and the high oxygen tension technique to speed up decompression is the combined use of both techniques. The use of alternation of inert gases in the breathing mixture, combined with fluctuation of high oxygen tension, continues to occupy the research efforts of diving physiologists. As an example of the demonstrated capability of this advanced

decompression technique, a 5-time reduction of decompression time has been shown for a 300-ft, 60-minute dive.

(5) Drugs for Accelerating Blood Flow. The use of drugs has been suggested as a means of accelerating blood circulation in tissues during ascent to enhance the elimination of inert gases. The reverse effects--slowing up blood circulation during descent--would minimize inert gas take up. Although this technique is possible, no data are available to assess its possible contribution to the decompression problem.

b. Oxygen Toxicity

Pressure has a significant effect on a diver's oxygen requirements. Too much oxygen (hypeoxia) is almost as dangerous as too little oxygen (hypoxia). Short term exposure to high oxygen tension can affect the central nervous system, causing localized muscular twitching and convulsions; long term exposure to high oxygen tension impairs the process of gas exchange in the alveoli, or air sacs, of the lungs. The actual toxic effects of oxygen on the biochemical processes of the human body will probably not be known without many more years of research. A more precise definition of human tolerance to oxygen at high pressures must be known: (1) to select the best oxygen level, which varies with the duration, depth, and phase of the dive, and the muscular effort required for a dive; and (2) to maximize the use of oxygen to speed up decompression.

Experience to date indicates that the partial pressure of oxygen should be kept between about 150 and 400 millimeters of mercury (mm Hg) during the at-depth phase of a long saturation dive. The partial pressure of oxygen in the air we breathe at sea level is 160 mm Hg (21% of 760). If oxygen is kept at 21% of the mixture, however, its partial pressure increases with depth--rising to 1,127 mm Hg at 200 ft. As a result, the proportion of oxygen in the breathing mixture must be reduced as depth increases to maintain a partial pressure range of 150 to 400 mm Hg; therefore, the band of tolerable oxygen percentage narrows rapidly with increased depth. The need for increasing accuracy in the systems that analyze and control the breathing gas mixture for a long term saturation dive is clearly indicated.

c. Inert Gas Toxicity

Gases such as nitrogen and helium, which are biochemically inert in the atmospheric pressure environment, are not so under increased pressure conditions. Nitrogen, which is physiologically inert at sea level, has an anesthetic effect under pressure. At depths greater than 100 ft, the average diver will suffer effects of nitrogen narcosis. The effects are impairment in judgment and psychomotor ability, which can render a diver completely unable to cope with emergencies. Helium has been found to be much less narcotic and is currently used instead of nitrogen in almost all deep-sea dives. Some experiments are also being conducted to determine the narcotic effect of hydrogen, since there are indications that hydrogen has even less narcotic effect than helium. There is experimental evidence that the limit due to helium narcosis may be in the region of 1,000 ft. There is on-going experimentation in the use of oxygen-hydrogen and oxygen-hydrogen-helium mixtures for depths greater than 1,000 ft. Experimental dives to depths of 1,500 to 1,800 ft are being planned by a European firm (COMEX).

d. Gas Density and Viscosity

Elevation of pressure on any gas mixture increases its density and viscosity. The increased density and viscosity of breathing gas results in increased resistance to movement of gas through the small respiratory passages. This resistance not only interferes directly with pulmonary ventilation but also increases the work of breathing itself. The use of helium in the breathing gas mixture reduces gas narcosis effects and circumvents some of the breathing resistance problems. Since nitrogen is about 7 times more dense than helium at 1 atmosphere, the density of nitrogen at about 200 ft of seawater is as great as that of helium at 1,000 ft. The major method for reducing respiratory resistance at very great depths will be the use of less dense and less viscous gases, such as helium or hydrogen. A technological solution to the respiratory resistance problem might be the development of a respiratory pump. This pump will provide the necessary assistance in the work of moving air in and out of the lungs.

e. Temperature

The human body can maintain its thermal equilibrium only within very narrow limits. Both high and low temperatures represent human physiological limitations. In water above normal body temperature, fever develops even at rest, and exercise accelerates the onset of fever. In water below normal body temperature, the unprotected man will lose heat about 21 times faster than he would in normal air at the same ambient temperature. Metabolic heat produced by exercise extends the tolerance to cold water, and the combination of insulation (wet suit) and work provides useful periods of time in water at temperatures down to 55°-60°F. Significant improvement in human temperature tolerance cannot be expected from the use of drugs or physiological adaptation. Rather, human temperature tolerance must be achieved by the use of insulating and external heating methods properly integrated with the understanding of physiological heat exchange.

f. Hydrostatic Pressure Effects (Pressure Syndrome)

If the problems of decompression, oxygen toxicity, inert gas toxicity, gas density and viscosity, and temperature can be circumvented through physiological research and technological improvements, the final barrier to man's attempt to go deeper into the sea is the direct effects of hydrostatic pressure. Whereas the effects of pressure on human cellular structure and the resultant body functional impairments are essentially unknown, experiments have been conducted with animals and animal tissues that indicate the existence of direct pressure effects. A major difficulty in studies of this type is the inability to isolate causes of observed effects. For example, deterioration of mental performance, which is ascribed to helium narcosis, might be only the onset of pressure effects on the nerve cell structure. Tremors, sweating, dizziness, and redness in the face, which might be ascribed to carbon dioxide, could be direct effects of hydrostatic pressure.

In any case, it has been demonstrated in recent decades that hydrostatic pressure effects include: (1) failure of gel formation, (2) failure of cell division, (3) failure of ameboid movement, (4) inhibition of biological luminescence, and (5) inhibition of the growth of bacteria. Most of these effects appear to be related to the volume changes in cells. It is important to diving physiologists that bacterial growth is inhibited by pressures as low as 1,000 ft of sea water. This effect suggests the possibility that hydrostatic pressure has some influence at the depths where man still hopes to live for long periods. Recent simulated and operational deep ocean dives (greater than 600 ft) have indicated some pressure effects on bone-muscle structures. Divers working at depths exceeding 600 ft have shown susceptibility to dislocated joints. Although the number of incidents cannot support firm conclusions, there appear to be some bone-muscle effects resulting from high hydrostatic pressures that must be investigated.

2. Technological Research and Development

Research and development efforts in diving technology can be separated into two categories. The first is associated with the life support aspects of technology, that is, the hardware or systems that are needed to maintain the physiologic environment that is essential to sustain life in the ambient ocean pressure. The second is associated with functional support of man, that is, the hardware or systems that aid man in accomplishing undersea tasks (e.g., diver tools, communication equipment, navigation equipment, sonar, television, and propulsion aids). The following discussion deals only with life support technology. The identification of the requirements for functional support technology is, in fact, the objective of the overall MAN-IN-THE-SEA Program.

The focus of current R&D efforts in life support technology is in the following areas.

a. Individual Life Support Elements

It was indicated in the description of the physiological problems of diving that increasing diving depth is placing more stringent requirements on the makeup of breathing gas mixture and the monitoring of gas concentrations. The physiological effects of oxygen, inert gases, and contaminants are generally proportional to partial pressure rather than to percentage concentration. Since the partial pressure is the product of concentration and total pressure, the allowable concentration of any substance becomes smaller as diving depth is increased. For example, at 100 ft, the range of oxygen percentage is 3.75% to 7.50% and carbon dioxide percentage is 0% to 0.50%. At 1,000 ft, the oxygen percentage is 0.48% to 0.97%, and carbon dioxide percentage is 0% to 0.06%. Reliable devices for sensing, monitoring, and controlling the gas environment at high pressure must be developed. Moreover, methods of detecting and eliminating contaminants, such as carbon monoxide, must be developed. Unless atmospheric gases can be reliably controlled, full exploitation of the diving capabilities of man will not be possible.

Closely related to the development of reliable sensing, monitoring, and controlling devices for providing a safe breathing gas environment at high pressure is the continuing development of a reliable and safe closed circuit, mixed gas, self-contained underwater breathing apparatus. Present day breathing devices are limited in depth-time capability because of the need to exhaust portions of the breathing gas during each breath. The open or semiclosed SCUBA devices do not fully exploit the full amount of gas a free swimming man can carry. The totally closed circuit oxygen rebreather is limited in depth because of the problems of oxygen toxicity. The following paragraphs describe briefly the current devices in the U.S. Navy inventory and in research and development.

(1) Standard SCUBA. The demand, or open circuit SCUBA is a military version of the commercial device used by sports divers. The system is open circuit in that expired gases are discharged into the water during exhalation. Normal compressed air is the breathing gas medium; however, it is possible to use mixed gases for deep dives. Open circuit systems are inherently wasteful of gases. About three-fourths of the oxygen in each breath drawn from the gas cylinder is discharged into the water. The principal component of the open circuit SCUBA is the demand regulator, which releases compressed gas to the diver during the inspiratory cycle. A pressure regulator maintains the breathing system at ambient depth pressure; the regulator opens to create a slight negative pressure at the start of inspiration and remains open until the end of inspiration.

(2) MARK VI SCUBA. The MARK VI SCUBA is a semiclosed circuit, mixed gas breathing device. The gas mixture can be oxygen-nitrogen or

oxygen-helium, depending on the diving depths required. A volume of gas mixture flows from storage cylinders through a regulator into an inhalation breathing bag. Exhaled gas is then forced through a carbon dioxide removal canister and back into the inhalation bag. As oxygen is used up in the breathing volume (inhalation bag), a critical level is reached whereupon a fresh volume of gas mixture is transmitted from the storage cylinder to the breathing bag. The waste gas is then exhausted into the sea. The recirculating breathing apparatus allows a maximum utilization of available oxygen, thereby increasing diving duration. However, the need to exhaust inert gases still limits the useful dive duration.

(3) Closed Circuit Oxygen SCUBA. The closed circuit oxygen SCUBA, which is issued primarily to underwater demolition teams, employs a breathing device similar to that of the MARK VI. However, pure oxygen is used as the breathing medium rather than mixed gases. The device can be used only to depths less than 30 ft because of the oxygen toxicity problem. The primary purpose of such a device is to maximize convertness; no waste gas needs to be exhausted into the sea, thereby eliminating telltale bubbles.

(4) MARK VIII SCUBA. The MARK VIII SCUBA is similar to the MARK VI SCUBA in that it is a semiclosed circuit device. The MARK VIII, which was developed specifically for the SEALAB III experiment, will use an oxygen-helium gas mixture. The gas can be supplied through hoses from the habitat or from diver carried cylinders. In the tethered mode a maximum duration of 3 hours at 600 ft can be achieved, using a single charge of baralyme in the carbon dioxide absorbent canister. In the free swimming mode, two 90 ft^3 cylinders provide sufficient gas for 1 hour at 600 ft.

All of the breathing apparatus described above is constrained in depth-time capability by the need for a premixed gas supply stored in swimmer carried cylinders of gas supplied through hoses. A closed circuit device where breathing gas is mixed on-site is being developed to extend the depth-time capabilities of current breathing apparatus. The success of such a system will depend on the development of a compact, rugged, and reliable oxygen sensing and flow control device that can maintain oxygen content within the narrow safety boundaries. A closed circuit mixed gas SCUBA is currently being developed for the Navy. The depth-time capability of the SCUBA might be extended through the use of cryogenic gas storage concepts. While cryogenic storage and gas mixing techniques are being developed, no information is available at this time.

Development of heated diving suits will be essential to the achievement of extended diving operations. Open circuit, hot water suits have been used successfully in the past few years. A battery supplied resistance wire heat suit was tried during the SEALAB II experiments but it is limited by the available energy-density of the battery pack. A nuclear isotope hot water heater, combined with the open circuit hot water suit concept, was scheduled to be tried during the SEALAB III experiment. The base of the heated suit problem is in the development of a compact energy source, which is a technological area that is receiving major research attention for many application areas.

Ancillary equipments being developed to support divers include advanced head gear, depth gauges, and decompression computers.

b. Operation Life Support Elements

In addition to the individual diver life support element, life support elements are required for the overall diving operation. From the viewpoint of technological research and development the most critical part of the operational life support element is in the provision, monitoring, and control of breathing gas composition. This includes the required breathing gas supply for the diver at working depth and for the stages of decompression within the decompression chamber during diver ascent to surface atmospheric environment. As was shown in the discussion of the physiological research area, the precision of control of gas composition increases greatly with increasing diving depth. Furthermore, since the diver's sensitivity to contaminants also increases greatly with increased diving depth, extreme care must be exercised in making up the breathing gas supply. The major technological developments in the operational life support system element are focused toward achieving an on-site gas mixing capability. Current diving operations require the use of a premixed gas supply, which constrains its operational flexibility. The achievement of an on-site gas mixing capability revolves around the availability of reliable and portable gas analysis sensors so that the composition of the breathing gas can be controlled within the required tolerances.

3. Advanced Diving Concepts

Advanced MAN-IN-THE-SEA concepts reflect two developments aimed at sending man to deeper ocean depths for longer duration. These developments are the techniques of fluid breathing and the use of artificial gills for gas exchange. Experimental evidence indicating that the mammalian lung can function as gills was presented in 1962. It was found that adult mice, rats, and dogs can live for prolonged periods of time submerged with lungs filled with fluid--in salt solutions equilibrated with oxygen at high pressures. Under these conditions the submerged mammals continued making respiratory movements and were apparently capable of extracting adequate amounts of dissolved oxygen from the aqueous environment. The animals were not killed by hydrostatic pressures of up to 160 atmospheres, which is equivalent to a depth in the ocean of 1 mile.

The potential practical importance of this phenomenon is clear. The problem of decompression sickness would be circumvented since the inert "filler" gas would no longer be present. No inert gas would dissolve in the blood, and tissues of a diver with fluid-fill lungs; consequently, he would be free to ascend to the surface at any time and as rapidly as he desired without fear of bubble formation. The problem of inert gas narcosis would also be avoided. If the fluid breathing concept proves to be physiologically feasible in all ways, the depth that man can reach as a diver would be limited only by the effects of hydrostatic pressure on cellular structure. However, the use of the fluid breathing technique by humans is still far in the future because the physiologic effects of fluids on the lung tissues are still not known. Furthermore, gas exchange in liquid filled lungs is diffusion limited, and at least 60 times more work is required to propel equal amounts of water instead of air through the lung passages. These factors seriously restrict carbon dioxide elimination in water breathing mammals. In mechanically ventilated water breathing dogs, carbon dioxide elimination was always deficient. The use of fluid breathing techniques by man will come about only through extensive research into the effects of fluids on lung tissue and through the solution of the problem of carbon dioxide elimination.

Fish obtain oxygen for their metabolic demands by diffusion from the seawater in which they swim; they eliminate carbon dioxide in the same way. Diffusion takes place in the gills of the fish where water and blood are in intimate contact, separated mainly by a series of cell membranes. The same physical factors that operate to supply oxygen and eliminate carbon dioxide in fish gills, i.e., membranes with appropriate permeability properties, can be used in the design of artificial gills. An artificial gill, which could enable submerged men to obtain oxygen by diffusion from water, would have obvious advantages. Work on such gills has been carried out in several laboratories, and recently a U.S. patent was awarded to the designer of one. The problem of obtaining oxygen by diffusion from water is essentially one of developing a proper membrane. The membrane must permit passage of the oxygen molecules while restraining the water molecules. There are membranes in existence that would satisfy the diffusion requirements.

The ultimate system that would allow man to roam the ocean freely for long periods of time might come about by the combined use of the fluid breathing technique with the extraction of oxygen from seawater by artificial gills. The development of such a system is very far in the future and can result only through extensive R&D efforts.

D. Systems Configurations

1. Systems Options

A wide variety of configurational options is possible in integrating MAN-IN-THE-SEA components into an undersea work system. The selection of a particular configurational option is governed by the specific work site environment and task requirements. Seven generalized systems were configured to provide baseline systems for this study. These systems are categorized in terms of the support component employed in the system, i.e., surface ship support or submarine support. The seven options of MAN-IN-THE-SEA systems are listed in Table B-1, together with the identification of the principal components that make up the system. Each of the systems is illustrated and described in Figs. B-1 through B-7.

Table B-1

MAN-IN-THE-SEA SYSTEMS OPTIONS

MAN-IN-THE-SEA Systems Options	Principal MAN-IN-THE-SEA Systems Components								Notes
	Surface Support Ship	Subsurface Support Ship (Submarine)	Subsurface Support Habitat	Decompression Chamber	Personnel Transport Capsule (PTC)	Personnel Transport Vehicle (PTV)	Free Swimming--Personnel Support	Tethered--Personnel Support	
I Direct Surface Supported System (Fig. B-1)				1			2	2	1. Emergency use only 2. Either free swimming or tethered
II Augmented Surface Supported System--PTC (Fig. B-2)				3					3. On the surface support ship
III Augmented Surface Supported System--PTV (Fig. B-3)									
IV Augmented Surface Supported System--Habitat (Fig. B-4)					4	4			4. Either PTC or PTV
V Direct Subsurface Supported System (Fig. B-5)				5					5. On the submarine
VI Augmented Subsurface Supported System--PTV (Fig. B-6)									
VII Augmented Subsurface Supported System--Habitat (Fig. B-7)						6			6. Optional personnel transport

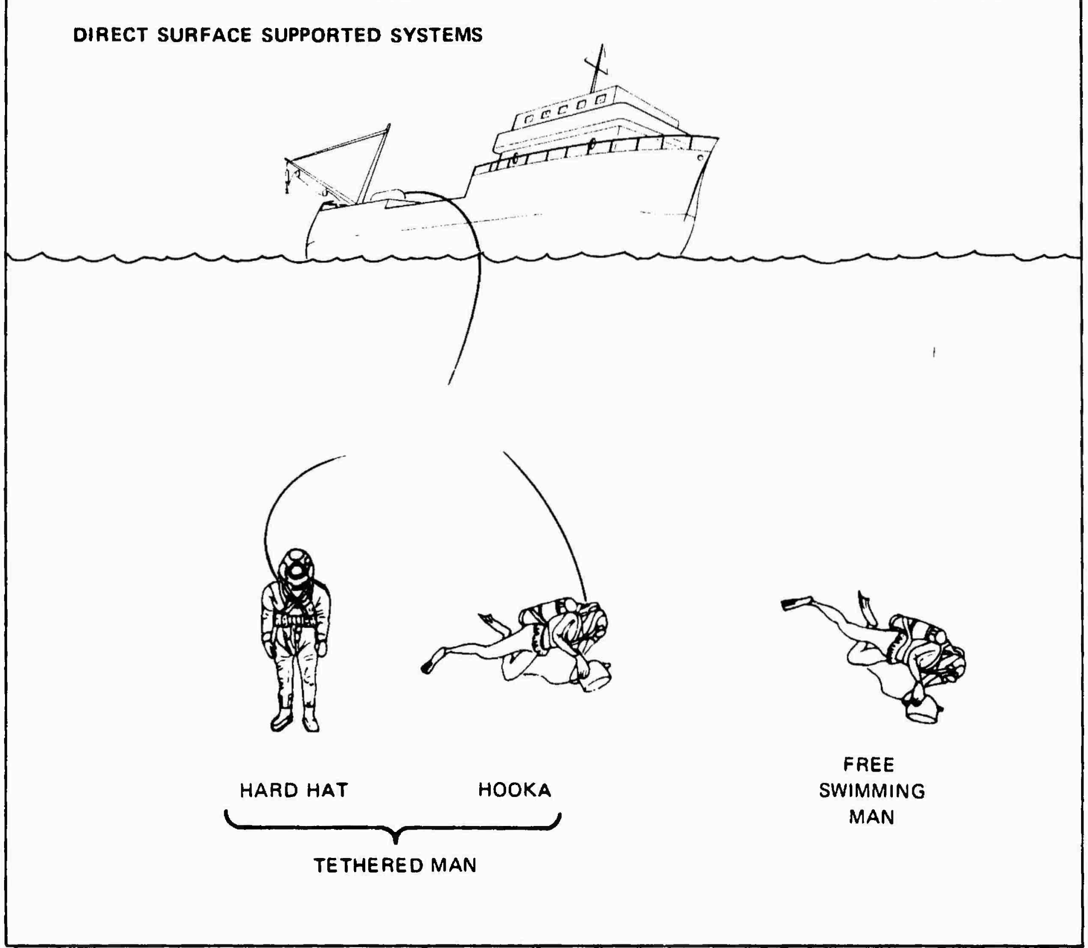

FIGURE B-1 MAN-IN-THE-SEA SYSTEM OPTION I

The most familiar form of a MAN-IN-THE-SEA system is the tethered or free swimming man operating directly from a surface support platform. The three specific forms of DIRECT SURFACE SUPPORTED SYSTEMS are described in the following:

The **Hard Hat** diver, tethered to a breathing gas supply on the surface ship, is the earliest form of the MAN-IN-THE-SEA system. The average diving depth for compressed air dive is 150-200 ft, the limit being established by individual susceptibility to nitrogen narcosis. Working dives to 300-350 ft can be accomplished with the use of a helium-oxygen mixed gas supply. The time limit is established primarily by the physical endurance of the diver. The primary functional limit of the tethered hard hat diver is his mobility and maneuverability.

The **Free Swimming** diver overcomes the mobility and maneuverability constraints of the hard hat diver. However, a compromise is made on diving duration. Time constraints are established by the limited life support stores that a diver can carry and his dependency upon the particular breathing system used. Standard open cycle air SCUBAs have a limited depth-time function. Closed cycle oxygen rebreathers are limited by oxygen toxicity to use above 33 ft, however, they possess time and covertness advantages over the open air SCUBA. Semiclosed mixed gas SCUBAs enable greater depth-time capability than either of the two systems mentioned above. An advanced closed cycle mixed gas system capable of 4-6 hr at 600 ft has just been introduced that overcomes many of the present day free swimmer limitations.

The **Tethered Swimmer** (Hooka) is a compromise solution to the mobility constraints of the hard hat diver and the time constraints of the free swimmer. The tethered swimmer is supplied by surface breathing gas stores of compressed air or mixed gases.

All three forms of the direct surface supported systems described above use the technique of ascent decompression. That is, the diver is required to remain in the water at predetermined depth stages and durations during ascent. Decompression facilities are on hand for emergency purposes.

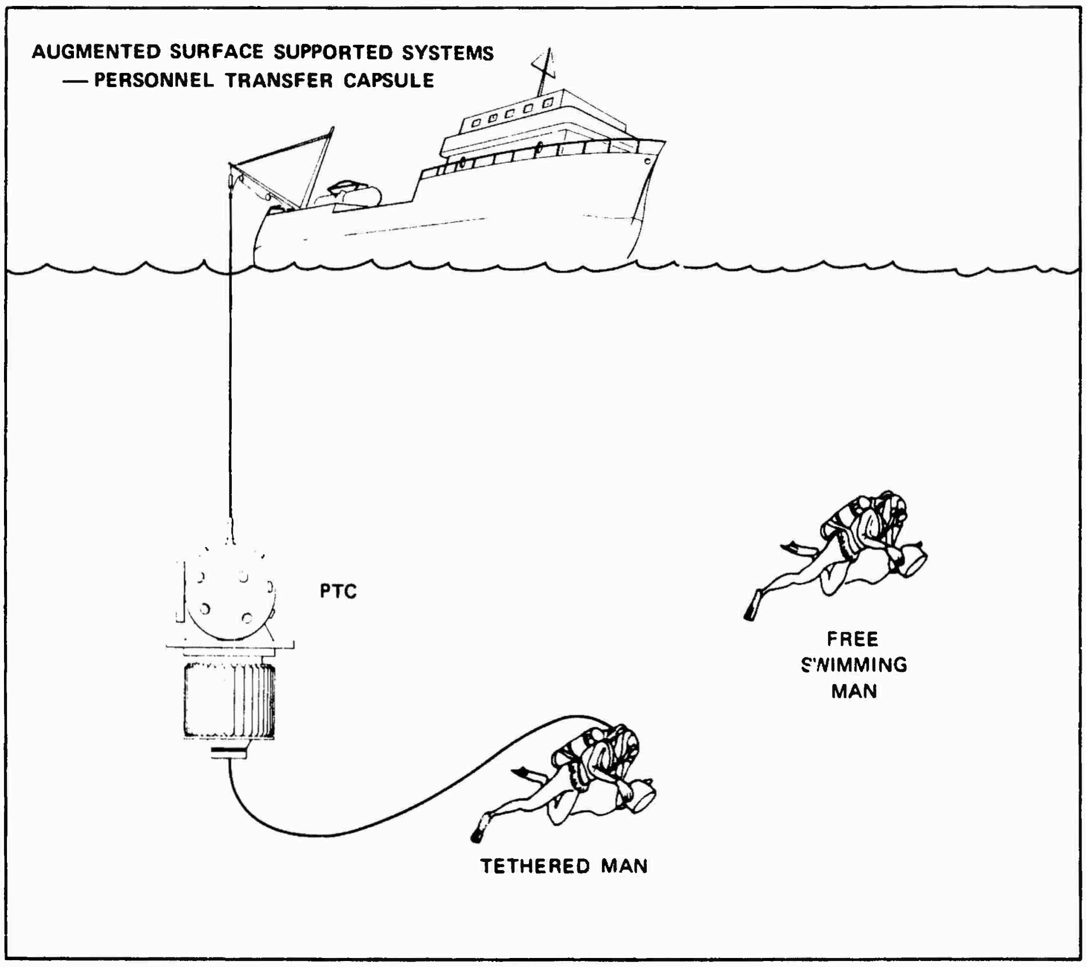

FIGURE B-2 MAN-IN-THE-SEA SYSTEM OPTION II

The first category of AUGMENTED SURFACE SUPPORTED SYSTEMS is one that uses the personnel transfer capsule (PTC) together with a deck decompression chamber (DDC) . The PTC serves a diving team as the transfer elevator to and from their underwater work site while maintaining a required pressurized breathing environment of compressed air or mixed gas. The PTC can be used in two ways. In its principal use, the capsule carries divers to the work site or to the spot from which diver excursions will be made. The capsule maintains the diver in an air or mixed gas atmosphere that has a gas pressure equal to the sea water pressure at the diver's destination depth. At the destination depth a diver may leave the capsule through a lower lock. The diver may operate out of the PTC on a tether that supplies breathing gas for long work periods, or he may use self-contained equipment as an untethered swimmer.

The PTC can also be used as a diving bell, with atmospheric air at surface pressure environment (14.7 psi). The PTC is used for observation and inspection of work or work site. If inspection establishes that divers are needed, the PTC can then be pressurized to ambient pressure and divers deployed for in-water work. There are major economic advantages to this way of using the PTC.

The DDC provides a pressurized environment aboard the surface support ship compatible with the ambient pressure condition of the work site. An entrance lock provides a pressure connection between the DDC and the PTC, allowing transfer of divers while maintaining their pressurized environmental conditions. In addition to its decompression function, the DDC also provides the function of a habitat for multiple dive operations. That is, the diver can make many trips between surface and work site without the need for decompression after each dive. He is maintained at work site ambient pressure in the DDC. Only one decompression cycle is needed after completion of the multiple dive operation. The terms "bounce dive" and "subsaturation dive" have been applied to the technique of decompression after each dive. The term "saturation dive" is used to refer to the technique of a single decompression cycle after a long term multiple dive operation.

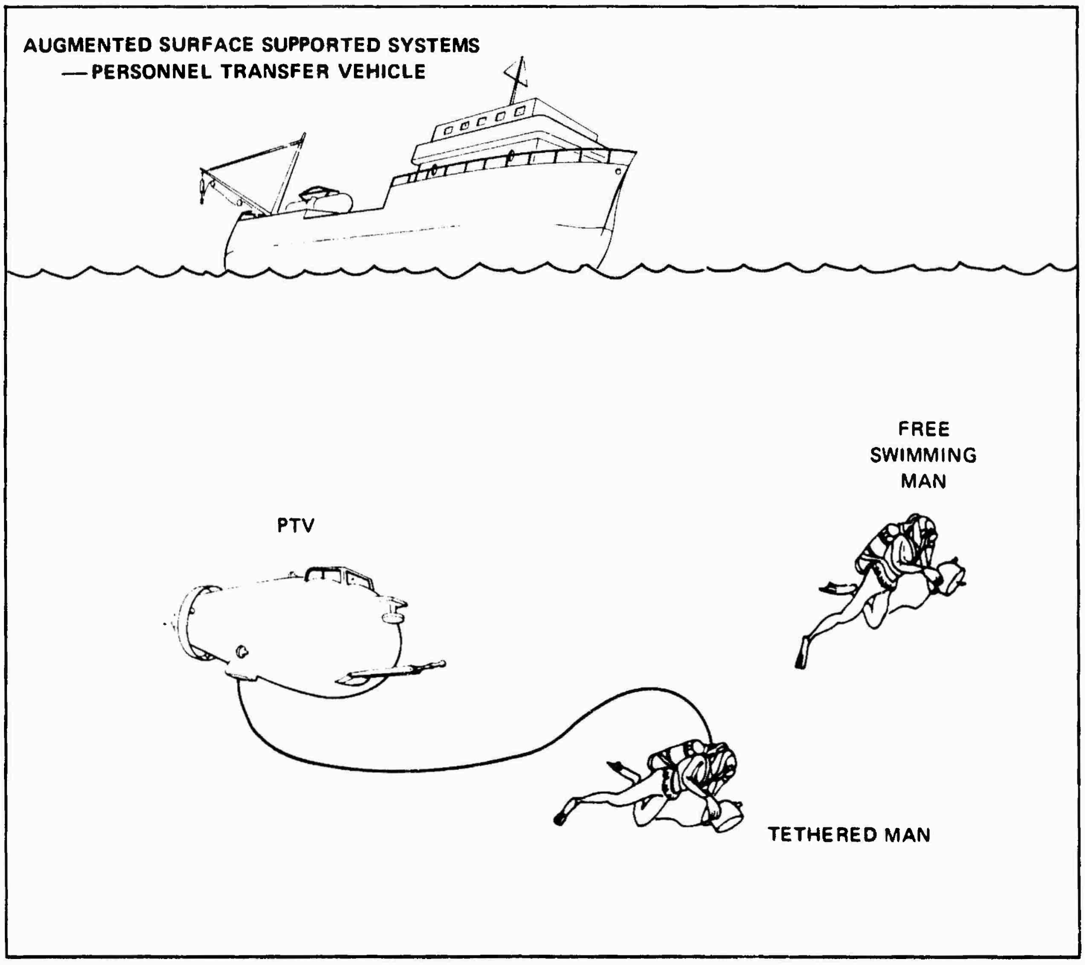

FIGURE B-3 MAN-IN-THE-SEA SYSTEM OPTION III

The second category of AUGMENTED SURFACE SUPPORTED SYSTEMS uses the personnel transfer vehicle, together with a deck decompression chamber (DDC). The PTV is used in the same manner as the personnal transfer capsule (PTC) described in the preceding system. The PTV has the advantage of horizontal movement over the PTC in its diver transfar and support functions. There are a number of operating vehicles today that have the diver delivery (lock-out) capability, specifically, the Ocean System, Inc., DEEP DIVER; the North American Rockwell, BEAVER MARK IV (ROUGHNECK); and tha Lockheed, DEEP QUEST, to name a few. The common feature of all PTVs is the use of an atmospharic pressure compartment and a diver lock-out compartment. Tha vehicle pilot and/or a technical observer operates from the atmospharic pressure compartment. Tha divers ara transported in the lock-out compartment.

The flexibility of this system lies in the fact that tha decision to use divers can be delayed until a thorough inspection is conducted and a work plan is developed in an atmospharic condition. Than without dalay, divers can ba deployed to do the work. The scheme eliminates unnecessary exposure of divers to ambient pressure with the accompanying long and costly decompression cycles.

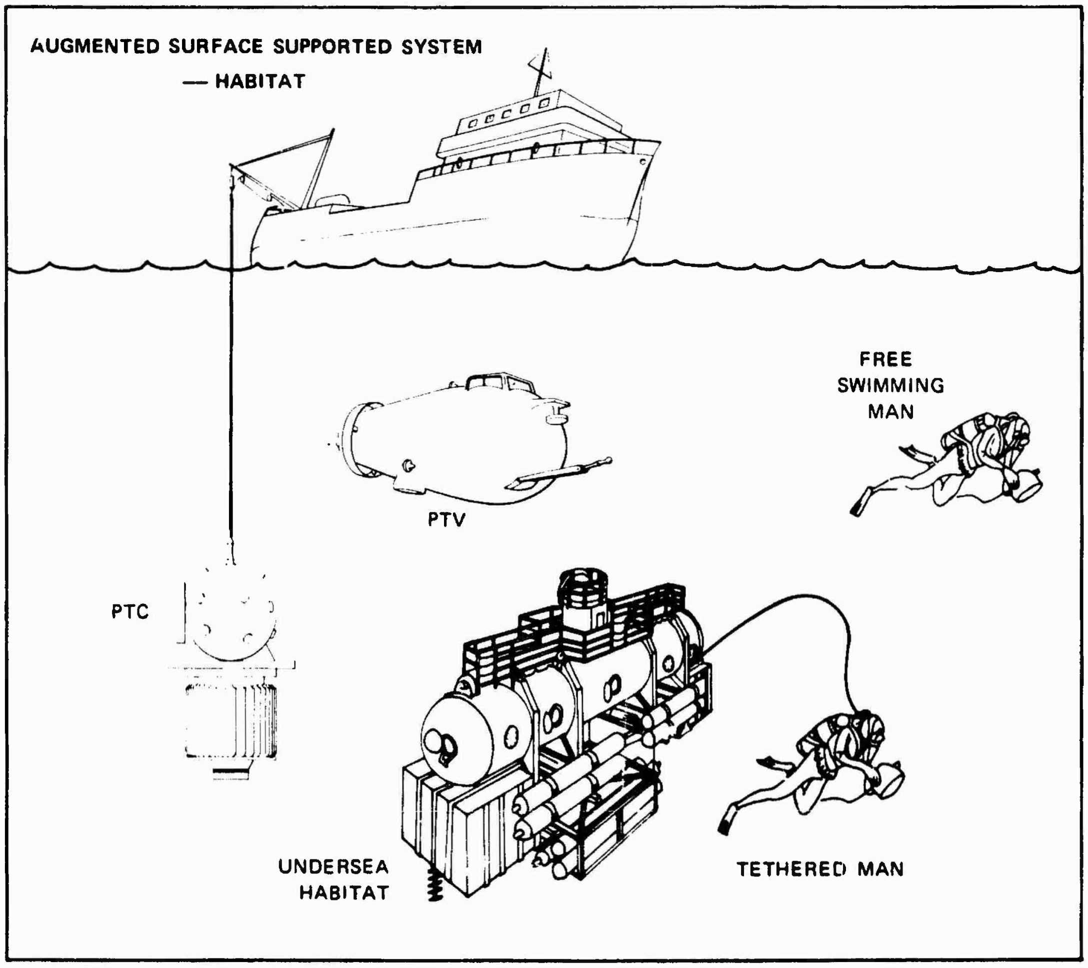

FIGURE B-4 MAN-IN-THE-SEA SYSTEM OPTION IV

The third category of AUGMENTED SURFACE SUPPORTED SYSTEMS employs an undersea habitat located at the work site. The habitat provides the living quarters from which men can make excursions to the job site. The habitat maintains an ambient pressure environment utilizing the required gas mixture for the specific operating depth (air or helium-nitrogen-oxygen mixtures). The use of the undersea habitat provides prolonged undersea work capability by: (1) capitalizing on the unique capabilities of saturation diving techniques, i.e., the improved ratio of on job time vs decompression time, and (2) reducing the dependence on surface support, which enables uninterrupted work in rough weather conditions.

In operation the habitat would be transported to the job site and emplaced by the surface support ship. Personnel could ride the habitat to depth or they could be delivered to the habitat by the personnel transfer capsule or the personnel transfer vehicle. After completion of the work cycle personnel are returned to the surface via the PTC or PTV and decompressed in a decompression chamber on the surface support ship. The personnel can also remain in the habitat and be decompressed in the habitat during recovery. The combined use of the habitat as a decompression facility has evolved a system referred to as the MOBILE HABITAT concept.

Examples of augmented surface supported systems are the U.S. Navy SEALAB systems, the TEKTITE system , and the MOBILE HABITAT system of Makai Range, Inc.

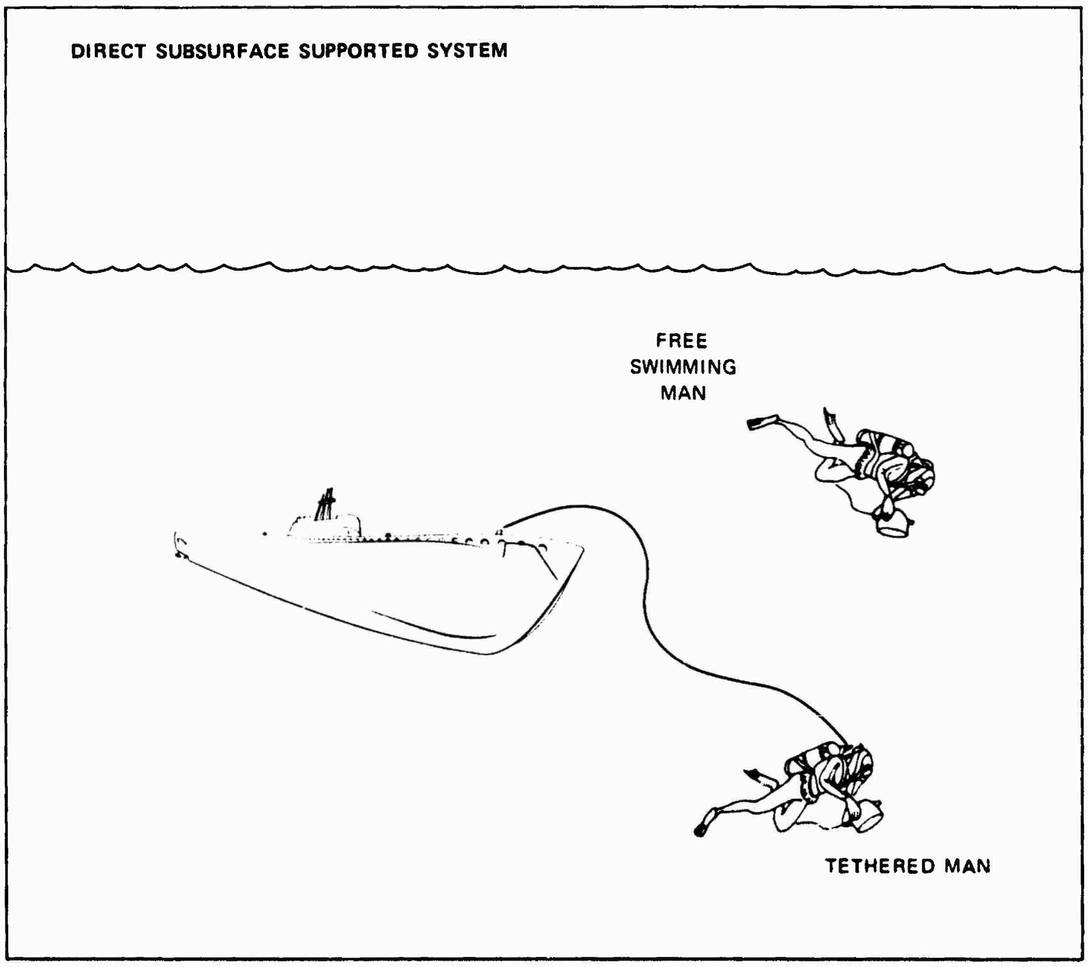

FIGURE B-5 MAN-IN-THE-SEA SYSTEM OPTION V

The DIRECT SUBSURFACE SUPPORTED SYSTEM is one in which personnel are deployed and supported from a submarine platform. The most familiar form of this system is the deployment of underwater demolition teams (UDT) from submerged submarines. An example of the system is the completed conversion of the guided missile submarine, USS GRAYBACK, into a swimmer transport and support submarine. The submarine is configured for the deployment and recovery of swimmers while submerged through the use of a "lock-out" compartment. The submarine is provided with a decompression chamber. In operation, personnel can be deployed in the free swimming or the tethered mode (see Figure B-1, MAN-IN-THE-SEA System Option I).

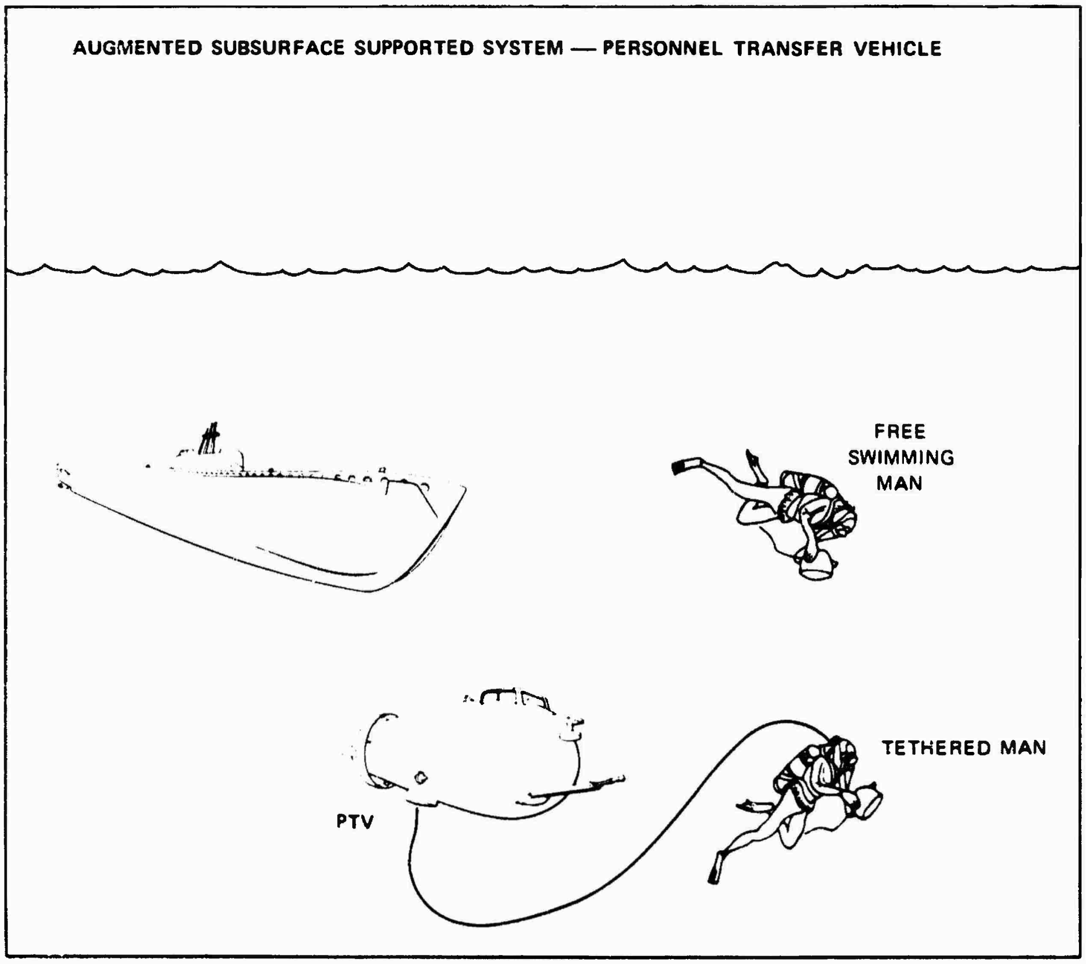

FIGURE B-6 MAN-IN-THE-SEA SYSTEM OPTION VI

The first category of AUGMENTED SUBSURFACE SUPPORTED SYSTEM uses the personnel transfer vehicle (PTV) as an auxiliary support platform. The primary purpose of the PTV is to provide support of personnel where the larger support submarine may be constrained, e.g., maneuvering space and water depth. The PTV will be transported and deployed from the submarine. Personnel can operate from the PTV in the free swimming or tethered mode as described for the surface supported system (see Figure B-3, MAN-IN-THE-SEA System Option III). The submarine will contain the required decompression facilities.

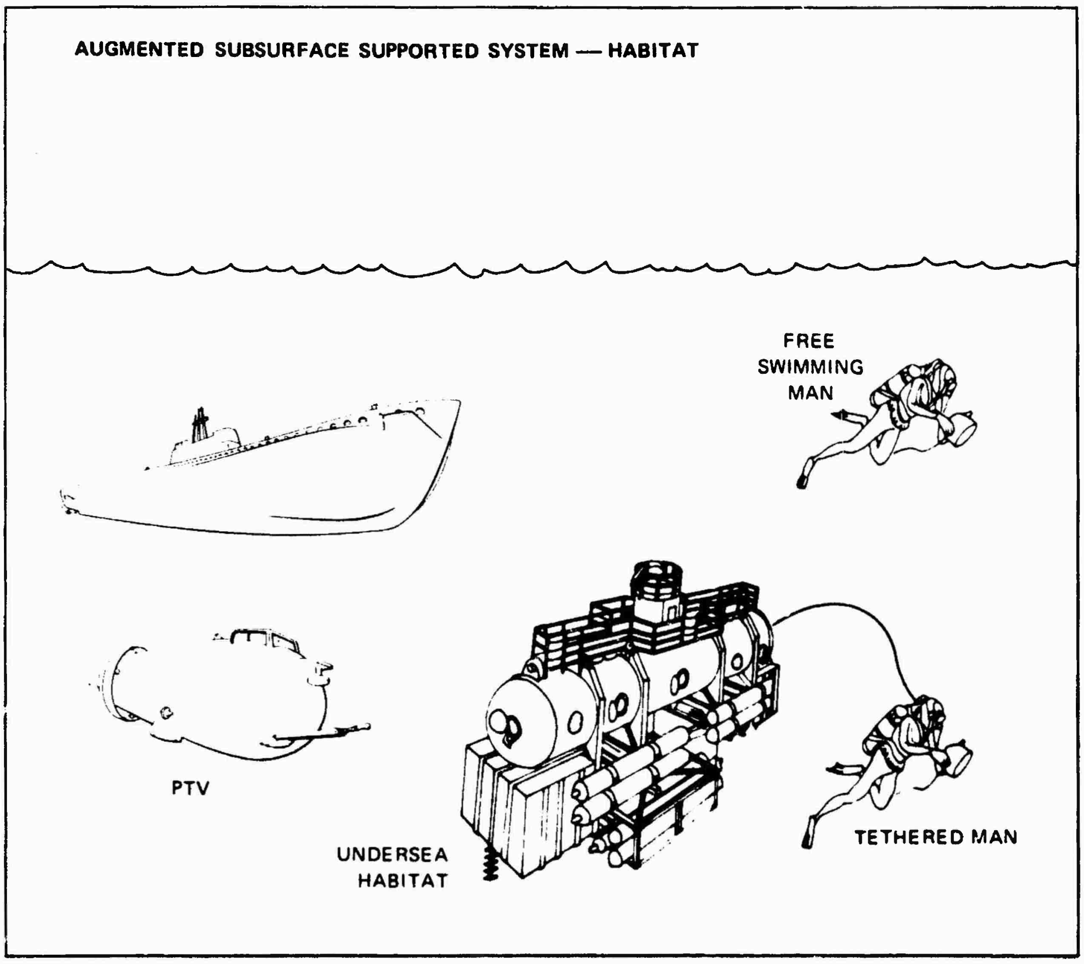

FIGURE B-7 MAN-IN-THE-SEA SYSTEM OPTION VII

The second category of AUGMENTED SUBSURFACE SUPPORTED SYSTEM uses an undersea habitat. The basic concept is similar to the surface supported system described in Figure B-4, MAN-IN-THE-SEA System Option IV, with the exception that a submarine is used to transport, emplace, and support the undersea habitat. The use of an auxiliary personnel transfer vehicle (PTV) is possible. In operation, the submarine will transport the habitat to the job site and emplace the habitat. The submarine can then leave the habitat and return for resupply, and, finally, the recovery of the habitat and work team. The submarine will be fitted with the required decompression facilities.

2. Surface Decompression Chamber and Personnel Transfer Capsule

The development of the surface decompression chamber in combination with the personnel transfer capsule capitalized on the capabilities of saturation diving. At present there are many operational systems, with depth capabilities varying from a minimum of 500 ft to a maximum of 1,000 ft. Most of these operational saturation diving systems are in support of the off-shore oil operations. Although one diving system differs from another in configuration and dimensions, the basic systems concepts are similar. In support of the U.S. Navy's salvage and submarine rescue requirement, a diving system of the sort described is being constructed. This system, called the DEEP DIVE SYSTEM (DDS) MARK I, is similar in concept to all other diving systems in operation. The following paragraphs describe the major components, the characteristics, and the operational sequence of the DDS MARK I.

The MARK I DDS comprises: (1) two deck decompression chambers (DDC), (2) an entrance lock, (3) a personnel transfer capsule (PTC), (4) a life support system, and (5) a main control console, as shown in Fig. B-8.

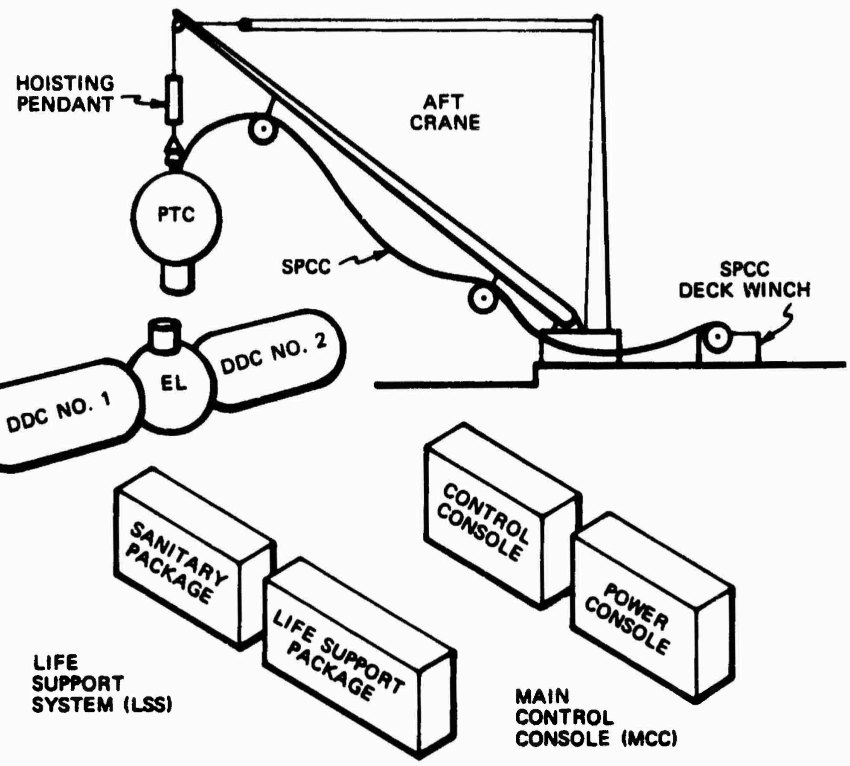

FIGURE B-8 MARK I DEEP DIVE SYSTEM

a. Deck Decompression Chamber

The MARK I system was developed for saturation diving, during which divers remain pressurized to their working depth for long periods and decompress only after completing multiple-dive objectives. The DDCs, which are shown in Fig. B-9, provide a pressurized environment aboard the ship compatible with the saturated condition of the divers. The entrance lock, which is located between the DDCs, provides a pressure lock between the DDCs and the personnel transfer capsule, allowing transfer of divers while maintaining their pressure saturated condition.

The entrance lock has its atmospheric system, which is similar to that of the chambers (it can be used as a decompression

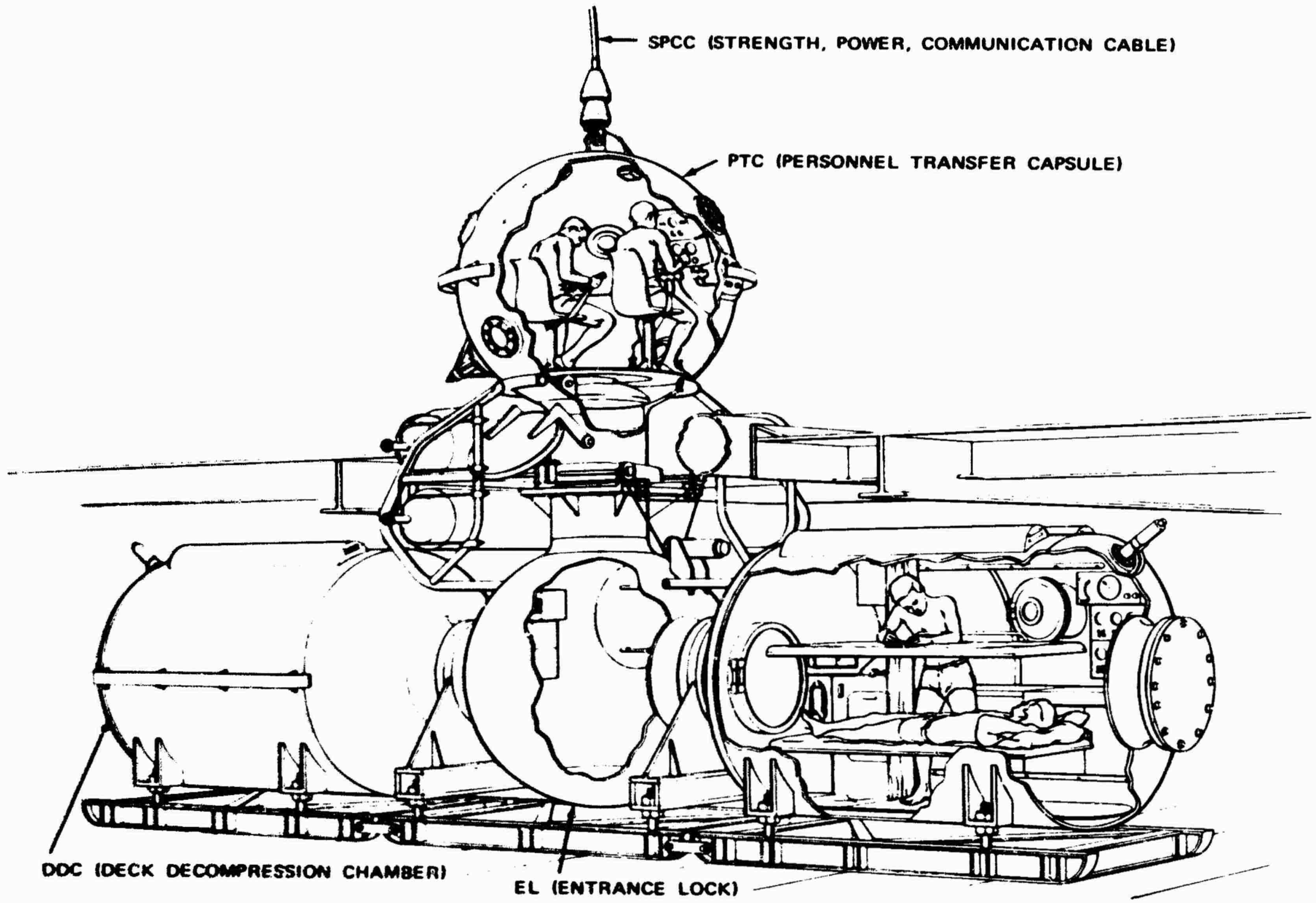

FIGURE B-9 DECK DECOMPRESSION CHAMBER

chamber in an emergency). It permits access between the DDCs and either the deck of the ship or the PTC.

The MARK I DDS complex consists of two DDCs connected to an entrance lock. The entrance lock is spherical and has four flanged-entry trunks with hatches as follows:

- Two trunks that attach semipermanently to the deck compression chambers

- A fourth flange that permits mating with the capsule in the horizontal position, which is required on some ships because of height limitations. This hatch also permits medical personnel to enter the complex as required.

b. Personnel Transfer Capsule

The personnel transfer capsule, the submersible of the MARK I DDS, serves the diving team as the transfer elevator to and from their underwater work site while maintaining the required pressurized environment. The configuration of the PTC is shown in Fig. B-10.

In its principal mode the PTC is used to carry divers from the DDC complex aboard the ship to the work site or the spot from which diver excursions will be made. In this mode the capsule maintains the divers in an artificial atmosphere that has a gas pressure equal to the ambient seawater pressure at the divers' destination depth. When used on working dives it can carry two or three divers at internal saturation pressures equivalent to 850-ft depths. At final equipment depth a diver may leave the capsule through the lower lock and be sustained on "hooka" lines at distances up to 100 ft.

The capsule can also be used as a diving bell, with atmospheric air at surface pressure of about 15 psia. In this mode it is used only for observation, and, of course, the occupants remain inside the

HEIGHT-OVERALL	144 in
DIAMETER	79 in OD
MATERIAL OR CONSTRUCTION	HY80
CAPACITY	2 MEN
DURATION	30 hr
DEPTH	850 ft

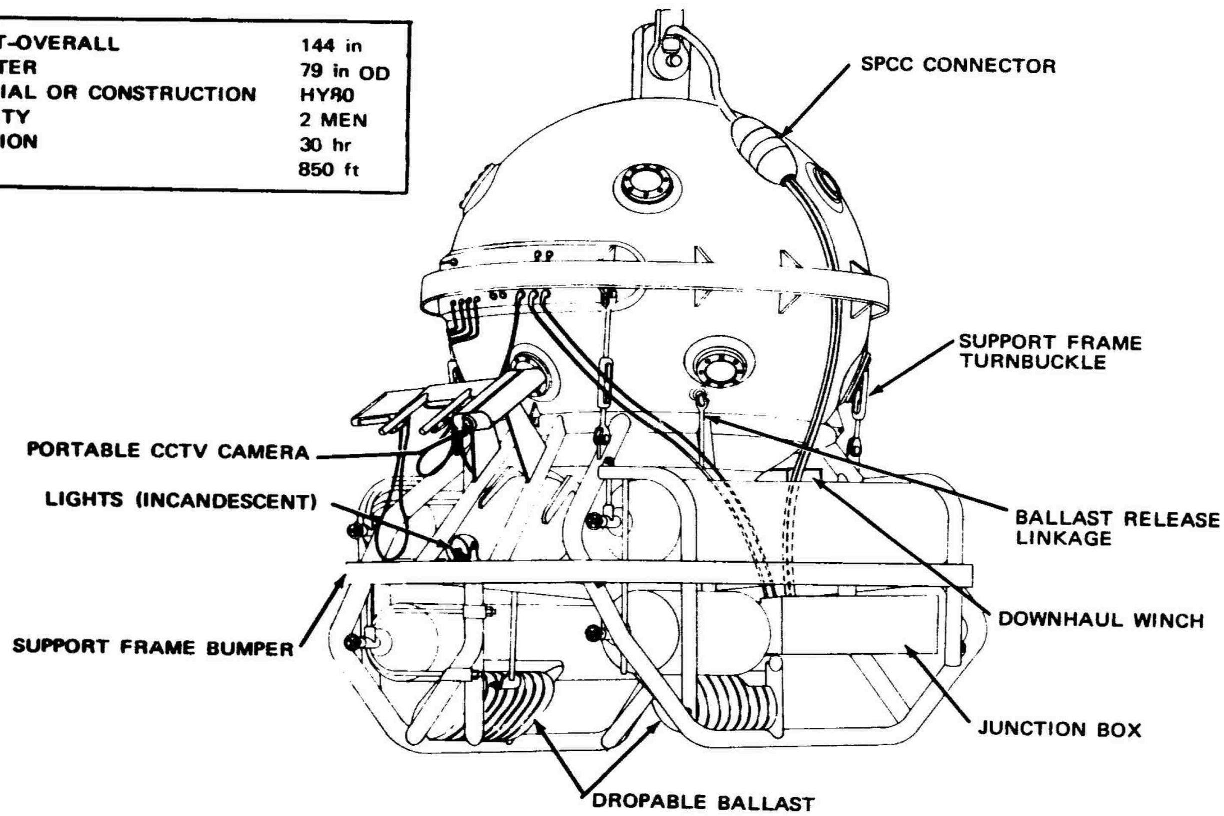

FIGURE B-10 PERSONNEL TRANSFER CAPSULE

vessel. In the diving bell mode the capsule can make sighting dives to depths of 1,000 ft.

A typical sequence of operation during a saturation dive using the MARK I DDS is shown in Fig. B-11.

3. Personnel Transfer Vehicle

The surface tethered personnel transfer capsule with the working diver tethered to the capsule is constrained from the viewpoint of mobility. A development designed to increase the mobility of the diver is the free swimming deep submergence vehicles equipped with diver lockout/lockin capability. The deep submergence vehicle can be viewed as a mobile PTC. As visualized, the diver delivery vehicle will work in conjunction with the deck decompression chamber. Transfer from vehicle to the DDC might be via a tethered PTC. This transition step would eliminate the need to lift and attach the deep submergence vehicle to the DDC. Current operating vehicles with diver lockout capability are the Ocean Systems, Incorporated, DEEP DIVER vehicle, the North American Rockwell BEAVER MARK IV vehicle, and the Lockheed DEEP QUEST vehicle. The BEAVER MARK IV vehicle configuration is shown in Fig. B-12. The forward operator compartment is maintained at atmospheric pressure throughout the operation. The aft compartment and the diver transport compartment are maintained at atmospheric pressure during transit to the work site. If divers are needed to complete the job, the aft compartment is pressurized to ambient pressure. A diver then opens the bottom hatch and swims out to the job. The diver can either be free swimming or tethered to the vehicle. This choice depends primarily upon the job's duration.

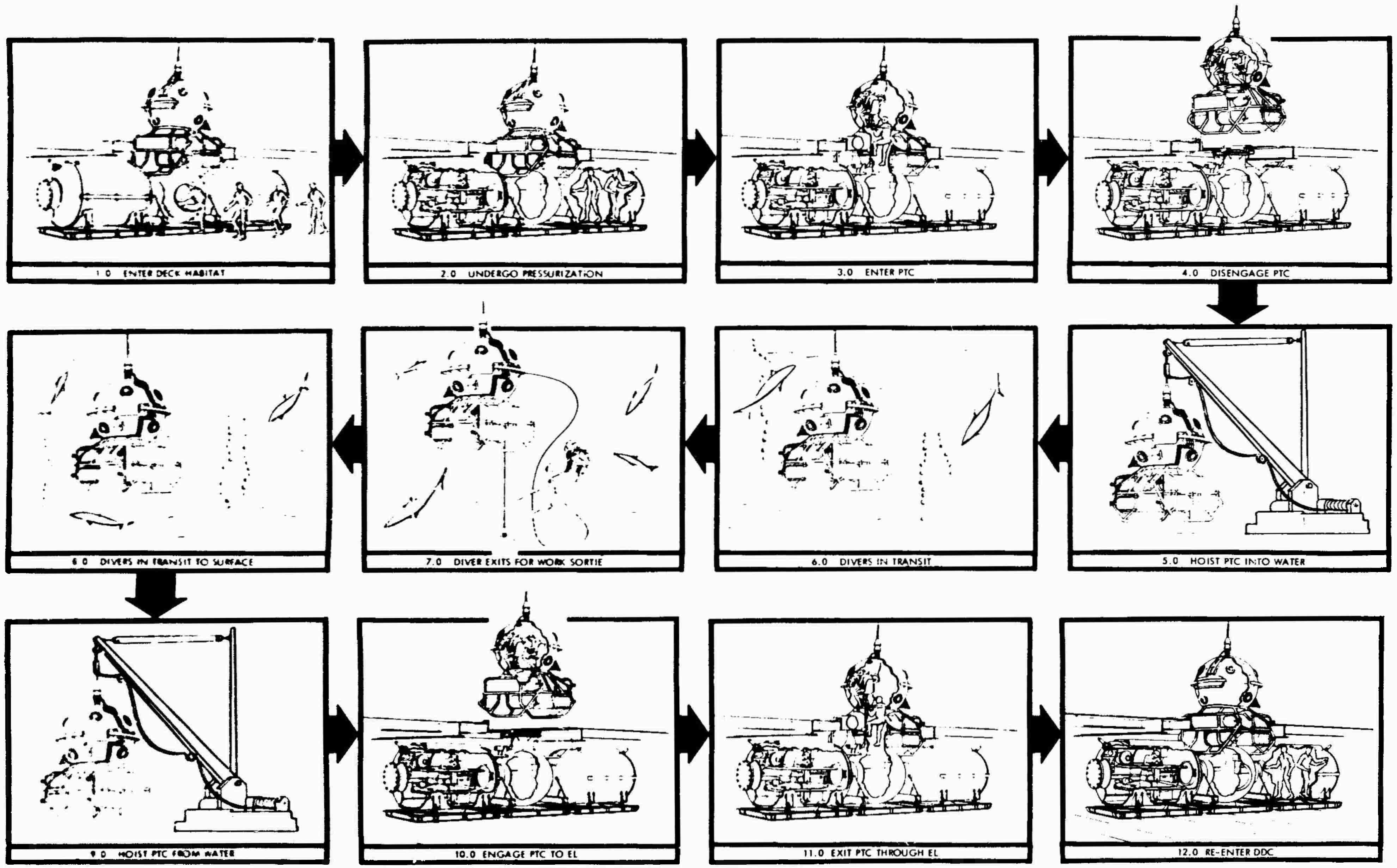

FIGURE B-11 MARK I DEEP DIVE SYSTEM OPERATIONAL SEQUENCE DURING SATURATION DIVE

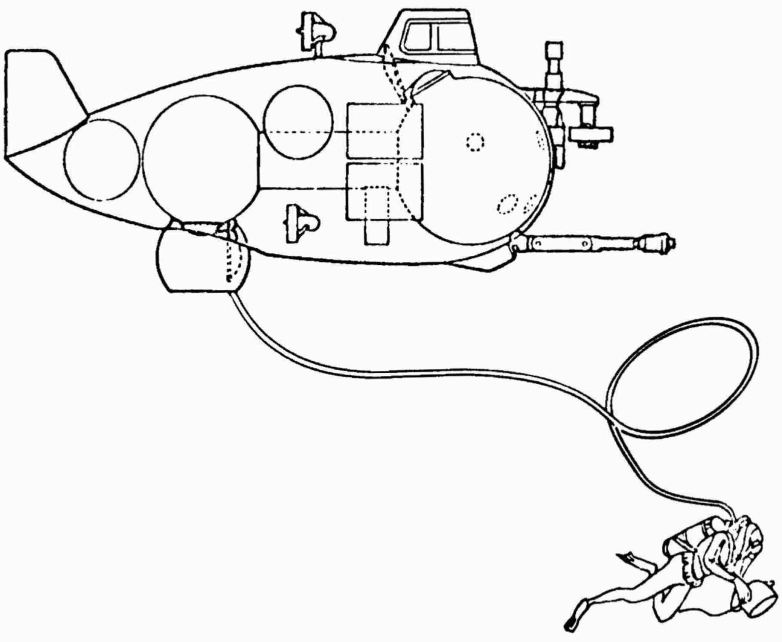

FIGURE B-12 MOBILE PERSONNEL TRANSFER VEHICLE

4. Fixed Bottom Habitat

A more advanced fixed bottom habitat approach has been suggested for the support of off-shore oil recovery operations. One of the more recent ideas is one suggested by Ocean System, Incorporated. This concept for off-shore oil drilling and production operation is illustrated in Fig. B-13. The basic element is a 40-ft-diameter, buoyant, double-walled sphere located between 100 and 150 ft underwater. In a typical installation a capsule would permit drilling and completion of nine producing wells, eight injection wells, and a spare well slot. The interior of the submerged sphere would be pressurized with a mixed gas atmosphere to the ambient pressure environment. It would enable men to work in a shirt sleeve environment on a regular shift basis.

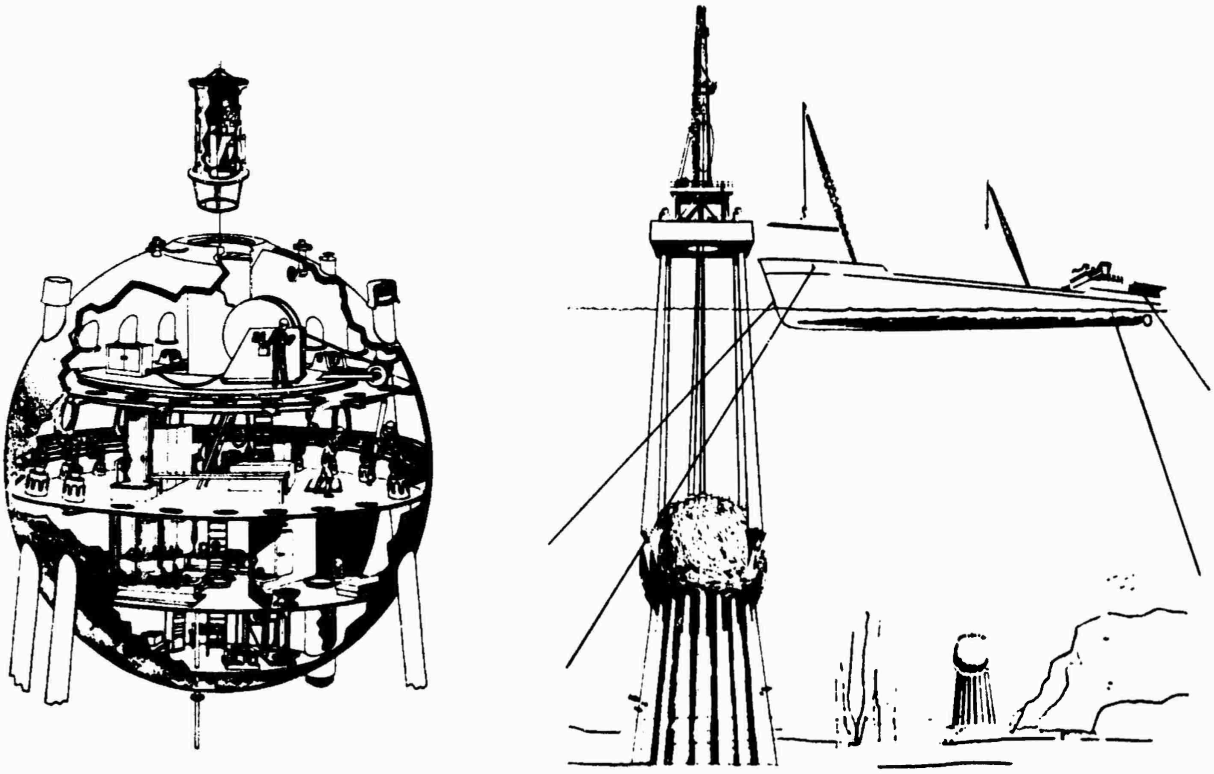

FIGURE B-13 ADVANCE OFF-SHORE OIL RECOVERY SYSTEM EMPLOYING MAN-IN-THE-SEA CONCEPTS

E. Performance Capabilities of MAN-IN-THE-SEA

1. Psychomotor Performance

a. Effects of Water Temperature

In general, it has been found that precision of fine dexterity manual performance deteriorates as water temperature decreases (Ref. 1).* It has been noted that the same task performed in SCUBA diving dress on dry land and in 70°F water shows a performance-time increase in water of 23% (Ref. 1), ascribed simply to the "various impediments . . . incurred" by being submerged. Subjects in the experiments cited performed all tasks bare handed and did not wear gloves during any part of the experiment. Thus, their hands were continuously exposed to the ambient environment. It was further noted that as water temperature decreases, performance decreases; the experimenters postulate ". . . a point somewhere between 54° and 60°F below . . . produces a rapidly increasing crippling of performance." These results were obtained at a single, shallow depth (25 ft) in a tank, the divers breathing normal air supplied by self-contained underwater breathing apparatus. Thus, the possible effects of depth pressure and gas mixtures were not considered in these experiments. Bowen and Pepler's (Ref. 1) postulated critical temperature ". . . somewhere between 54° and 60°F . . ." is supported by the earlier findings of Clark (Ref. 2) in studying the effects of hand skin temperature (in air) upon knotting performance (requiring very fine finger dexterity), observed severe degradation at 55°F; he further noted that ". . . performance decrement at that temperature increased exponentially with exposure duration, becoming asymptotic after about 40 minutes. Contrastingly, performance at 60°F hand skin temperature remained uneffecting throughout the exposure period" (sic).

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* References appear at the end of each appendix.

In the most definitive study of water temperature effects on motor performance yet reported (Ref. 3), finger dexterity deteriorated much more markedly than did ability to carry out tasks requiring relatively large movements of grosser muscle groups at the lowest of three temperatures (70°, 60°, and 50°F). Moreover, fine dexterity performance tended to deteriorate earlier during the 1-1/2 hour immersion period; both types showed a tendency to reach an asymptotic level well before the end of the period. This conclusion elaborates and probably further supports Bowen and Pepler's critical temperature assertion, as well as Clark's observation. Stang (Ref. 3) further shows that performance of all tasks at the other two temperatures (70° and 60°F) remained relatively stable through time but were significantly affected by the actual difference between thermal levels. His subjects worked in a small volume tank at 8-ft water depth, breathing normal air from SCUBAs. No dry land data were taken to show deterioration resulting from the water immersion effect; practice on all experimental tasks was provided at 60°F.

b. <u>Effects of Pressure and Water Immersion</u>

To set a baseline for evaluating their subjects' underwater performance, Bowen and Pepler had them perform the same tasks on dry land that they performed in the experimental tank. While the ambient temperature of the dry land environment is not reported, the authors note that to a diver in a wet suit (as their subjects were), 70°F water feels warm. Thus, the significant decrease in performance found between dry land and 70°F immersion is attributed "simply to being in the water," which was 25 ft deep (equivalent in fresh water to 1.75 atmospheres or 25.8 psi). Hill (Ref. 4) in studying the dry land and underwater performance of engineer-diver teams working on "routine service jobs" replicating oil and gas production facility maintenance operations, found a highly significant deterioration of performance at a 30-ft depth in a tank of

65°F water. Tasks carried out apparently included various combinations of fine and gross dexterity and probably some total body movement. Since no statement is made about diver equipment utilized, it is not possible to assess the encumbering effects of wet suits, SCUBA tanks, gloves, breathing gas, and the like. The author surmises that part of the difficulty experienced by his subjects in using hand tools, especially a hammer, rose from visual distortion (due to air-water mismatch at the divers' face masks) and "poor stability in a near weightless state."*

In a series of experiments designed to study manual force production capabilities of SCUBA swimmers, Streimer, Turner, and Volkmer (Ref. 5) found that the lack of traction resulting from the swimmers' state of neutral buoyancy caused a significant decrease in the force applied to the turning of hand wheels of various diameters and in one- and two-hand pushing and pulling operations, when compared with forces exerted in "the normally tractive state" (sic; not otherwise described, but presumed to be on dry land). In another study (Ref. 6) the authors showed that work underwater was more time consuming than the same tasks done on dry land, with a mean increase of 35%, which is statistically significant. They concluded that the type of work performed was differentially affected by immersion (12-18 ft, 62°-64°F) times for upper torso work increased 32%, for gross body "translations" 61%, and for work requiring relatively fine manual dexterity, 78% to 100%.

With regard to the specific effects of hyperbaric gas pressures on performance (dry land laboratory conditions), Kiessling and Maag (Ref. 7) showed insignificant decrease in performance (modified Purdue Pegboard, requiring fine digital-manual manipulations) and that, after an initial decrease in effectiveness with increasing pressure, performance

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* Assuming fresh water, the depth at which this experiment was carried out would exert pressure equivalent to 1.9 atmospheres, or 27.9 psi.

remains impaired but relatively constant, improving as pressure diminishes toward sea level. The experiments were performed in a pressure chamber at atmospheric pressures simulating a 100-ft water depth. Results were attributed to the narcotic effect of elevated partial pressure of nitrogen in the atmosphere (normal air). Subsequently, Baddeley (Ref. 8) compared the effects of simulated versus actual immersion depth pressures, concluding that manual dexterity is much more seriously impaired by 100 ft of seawater than by atmospheric pressure simulating that depth; he warns that it is ". . . unwise to generalize from pressure chamber experiments to underwater performance." During SEALAB II a number of strength and psychomotor tests were admin.stered before and during immersion to individuals and to teams; results showed systematically increasing deterioration of performance from dry land to shallow depth to habitat depth (Ref. 9).

To test the effects of depth further, Baddeley, de Figueredo, Curtis, and Williams (Ref. 10) administered two fine dexterity tests to divers in both open sea and pressure chamber environments, at depths of 5 and 100 ft, using compressed air as the breathing gas. Performances on both tests deteriorated slightly but significantly as depth was increased.

c. Effects of Gas Mixture

Baddeley and Flemming (Ref. 11) compared manual dexterity of divers at 10-ft and 200-ft depths, both in open sea and in a dry pressure chamber and breathing compressed air, and found that both air breathing and helium-oxygen mixed gas breathing divers showed a significant decrease in effectiveness at 200 ft in the sea compared with their performance at 10 ft. Further, helium-oxygen divers were significantly more accurate than air divers. In the dry chamber part of the experiment decrements that were concluded to stem from pressure alone were found for both types of breathing gas. The authors sum up by noting that ". . . 10 percent impairment in manual dexterity in a pressure chamber becomes a 30 percent decrement in the open sea," the effect being independent to a considerable extent of both depth and gas mixture (except that air induces greater impairment than helium-oxygen mixture).

d. Effects of the Nature of the Psychomotor Task

As previously noted, Stang (Ref. 3) showed that fine dexterity performance is more sensitive to deteriorative effects of immersion than is performance of grosser character. Bowen and Pepler's data (Ref. 1) analyzed for percentage performance decrements as a function of temperature at the long exposure values, tend to agree: a relatively gross manipulative test showed 11.25%, a finger dexterity test 19%, and a two-hand coordination test 100% decrement. The data of Streimer, Turner, and Volkmer (Ref. 6) suggest further agreement, in that fine dexterity work suffered 78% to 100% degradation, while gross movement tasks deteriorated from 32% to 61%. However, their findings suggest that in gross movement work those tasks that require the use of larger patterns of musculature may be subject to greater degradation than those requiring the use of smaller muscle groups: time to complete work requiring use of the upper torso increased only (from dry land times) 32%, while jobs requiring whole body movements took 61% longer. Results from SEALAB II individual assembly tests tend to agree with the initial formulation and further suggest that the more complex a manipulative task may be, the more it may be impared by underwater working conditions (Ref. 9).

2. Performance of Mental Tasks

a. Effects of Pressure, Gas Mixture, and Immersion

At an atmospheric pressure simulating 100 ft of seawater, using compressed air, Kiessling and Maag (Ref. 7) found that both choice reaction time and conceptual reasoning were significantly degraded compared with responses at sea level, and attributed the result to nitrogen narcosis. They noted further that when their subjects had been decompressed to an equivalent depth of 10 ft, allowing 100-ft compression, their performance returned to "approximately normal." Bennett, Poulton, Carpenter, and Catton (Ref. 12) tested 80 subjects on a card sorting task at sea level and at 33-ft (2 ats abs) and 100-ft (4 ats abs) pressures in compressed air and in 20% oxygen in helium. They reported significantly more errors at the 100-ft depth when subjects breathed air than when they breathed helium-oxygen; this effect was not found at the 33-ft depth. Moreover, subjects made significantly more errors when breathing air at 100 ft than at surface pressure. It was noted that all subjects worked faster and less accurately at 100-ft depth, regardless of breathing gas mixture, than they did at surface pressure. Authors attribute this to "an increase in the level of arousal at depth." Baddeley and Flemming (Ref. 11) found that, at 200-ft depths in the open ocean, divers worked more slowly at an arithmetic addition task than they did at 10-ft depths, regardless of whether they were breathing compressed air or helium-oxygen, but that only when breathing air did they show a marked increase in error rate (at 200 ft). Replicating their procedure in a dry pressure tank, they found evidence to support the conclusion that at a 200-ft depth the helium-oxygen breathing diver works slightly faster and considerably more accurately than the air breathing diver.

In another study (Ref. 10), Baddeley et al. found that a reasoning test using sentence comprehension showed about the same decrement between open sea depths of 4 and 100 ft, and in a dry pressure chamber simulating the pressures at those depths, the breathing gas being compressed air. The depth effect was significant, but the change from open sea to pressure chamber was not. The authors explain the former on the basis of nitrogen narcosis, the latter on the subjects' lack of apprehension about conditions surrounding the open sea diving phase.

During SEALAB II, arithmetic tests were given to the diver subjects; however, they were administered <u>inside</u> the habitat, under 200-ft helium-oxygen pressure saturation, rather than in the water under diving conditions (Ref. 13). The authors report a slight, probably not significant, improvement in performance compared with pre-SEALAB dry land trials.

b. <u>Effects of Temperature</u>

Bowen and Pepler (Ref. 1) had their subjects undertake two problem solving tests and one memory test, at water temperatures of 72° and 47°F, as well as on dry land. In all cases performance after long exposure at the lower temperature showed deterioration compared with similar exposure at the higher temperature, although the differences were not tested for significance. Stang (Ref. 3) had his subjects perform a choice-reaction procedure while solving problems in addition as a loading task; his data clearly show the deteriorative effects of diminishing water temperature: at 60°F reaction times were significantly longer than at 70°F, although at both temperatures they did not vary significantly throughout the 90 minutes. However, at 50°F there was sharp lengthening of reaction time for the first hour, followed by a leveling off at about 1-1/2 times the reaction times obtained at 70°F. This asymptotic performance at 50°F persisted throughout the rest of the experimental period and represented a highly significant degradation compared with the 70°F reaction time.

c. Effects of Emotional State

From the available literature it does not appear that controlled experiments have yet been performed relating the effects of induced emotional states such as task-induced stress in the form of anxiety. [See Hecker, Stevens, von Bismarck, and Williams (Ref. 14), for example.] However, several observers have reported behavior incidental to performance under water which they ascribe to emotional components. Baddeley (Ref. 8), in discussing the problems of open sea diver performance research, surmises that anxiety about personal safety, the reliability of life support equipment, and the effect of nitrogen narcosis may interact with experimental variables to contaminate results. Baddeley et al. (Ref. 10) in their later study of the effects of nitrogen narcosis again cite the probable complications resulting from emotional (i.e., anxiety) stresses associated with open sea diving, re-emphasizing the point made earlier by Baddeley and Flemming (Ref. 11) in their study of the performance of deep submergence helium-oxygen divers. In their assessment of SEALAB II divers' performance, Bowen, Andersen, and Promisel (Ref. 13) summarize results of a self-administered checklist completed several times by each member of each team during his 15-day submergence. Certain of the items were designed to enable measurement of anxiety or apprehension experienced by the individual; this class of response, called "fear" by the experimenters, was found to be positively correlated to a significant degree with another attribute, labeled "arousal," signifying reactivity to the SEALAB conditions and manifested by high variability between hyperactivity and withdrawal (lassitude, unwillingness to make sorties from the habitat, and the like). Further, "fear" and "arousal" were found to be negatively correlated, at a highly significant level, with time spent on diving missions and with number of sorties made, suggesting that the most active individuals were those who felt least tense and anxious about the SEALAB situations. In their study of perceptual narrowing in novice divers, Weltman and Egstrom (Ref. 15) reported that some of the subjects' reaction times to stimuli in the visual periphery were atypically prolonged and surmised that "their behavior appeared more closely related to diving risk than to other environmental factors." It is emphasized that the subjects in this experiment were, by the authors' definition, inexperienced, i.e., students. This study is unique among the work reviewed in connection with this project in that it attempted to assess the effects of emotional state on divers' performance under water. While the authors admit that their perceptual narrowing hypothesis is only partially "validated" by their results, they append to their report a bibliography that should not be overlooked in future research of this nature.

3. Sensation and Perception

a. Auditory

Included in the sensory testing program of SEALAB II (Ref. 9) were audiometric tests to determine effects of deep submergence environments on threshold hearing acuity. Conclusions resulting from analysis of the data are that divers' hearing levels tend to resemble those of people exposed to high intensity noise and that very little change in threshold acuity occurs for frequencies in the speech reception range (below 3,000 Hz), although there was a trend of hearing loss at the higher frequencies (above 3,000 Hz). (An experiment intended to assess underwater audibility of single frequency tones at 500 and 5,000 Hz, and binaural localization of tone sources by divers at SEALAB II depth, was not conducted, according to the authors, because of insufficiently powerful underwater sound transmission systems.)

Considerable laboratory work has been performed on the intelligibility of speech transmitted in compressed air and helium-oxygen environments, both over direct talker-listener paths and through electrical transmission systems. Divers' face masks and breathing apparatus are known to affect their speech, and, therefore, its reception, by other divers and surface support personnel. Available reports indicate that the severest problems lie in the areas of speech production rather than auditory reception. (They will be discussed under a specific "Communications" heading to follow.) However, it is appropriate to note here that aquanauts participating in SEALAB II (Ref. 9) reported that an apparent adaptation occurred during each 15-day cycle, in which the speaker seemed to become more intelligible as time went on; the divers attributed this to the lowering of voice pitch and a slowing down of speaking rate. The authors state that word lists and phrases recorded during the 45-day submersion period (presumably intended to measure the effects of hyperbaric helium-oxygen on speech) were to be carefully analyzed; however, no results of such analysis are reported in the SEALAB II document.

Auditory localization of underwater sound sources (such as homing devices or sources of potential hazard) is discussed in a report produced by CBS Laboratories in connection with describing an electronic device developed to augment human capability (Ref. 16). Although this discussion cites no specific experimental evidence or other publications, it argues that localization of sound sources by unaided underwater operators (swimmers, divers) is sharply limited compared with dry land capability because of the increased propagation-velocity of sound in water, transmission properties of the human skull, and the effects of reverberation and multipath propagation prevailing in the underwater environment.

b. Visual

The SEALAB II report also includes descriptions of water visibility measurements, both physical and psychophysical (Ref. 9). A device for measuring water clarity, developed by Scripps Institution, is briefly described (p. 251). A program for measuring aquanauts' visual acuity under water and an experiment for the detection and identification of 10 stationary visual targets, rectangular in shape and painted various colors as well as black and white, to be set at various distances and viewed from inside the habitat, are described under the heading "Uncompleted Studies" (p. 253). However, a study of target form and color visibility at the bottom was carried to completion (p. 251); results reported (p. 261, Table 30) show that a black circle 707 square centimeters in area was detected and recognized with significantly higher accuracy than the other three targets used: a 900-square-centimeter white square, a yellow triangle, and a white cross.

Underwater visual perception problems received increased attention following completion of SEALAB II in late 1965. The Navy's Submarine Medical Center has investigated a number of problems in areas delineated by Pauli and Clapper (Ref. 9); during the present study, several research reports were acquired from that center. They deal with basic problems of human ability to see in the underwater environment. One of these--the estimation of size and distance of unfamiliar objects (Ref. 17)--concluded that object size tends to be overestimated with increasing distance, both in air and in water (visual cues normally present were deleted as an experimental control), and also that in unstructured (i.e., cue-poor) visual fields estimates of distance between observer and object generally exceed the true distance. In another experiment (Ref. 18) it was shown that viewers' ability to resolve standard targets (Landolt Rings) was better underwater than on the surface (distances being identical for both conditions and apparent luminances being equated). Viewers wore SCUBA masks in both situations. Kinney, Luria, and Weitzman (Ref. 19) examined the visibility of various colors, both fluorescent and nonfluorescent, in four different bodies of water, ranging in clarity from very murky to clear. Targets were observed both by SCUBA divers underwater and by subjects on the surface looking down vertically. Fluorescent colors were found to be consistently more visible than nonfluorescent, but the visibility of specific colors depended on light transmission properties of the water. The significance of this study, from both theoretical and applicational points of view, lies in the careful measurements taken of total and spectral transmittance of water at the four test locations and in the development of a psychophysical color confusion matrix based on observers' judgments of all targets under all conditions. Luminance and chromaticity were specified for samples of all paints applied to targets used in the experiments.

In another study of color perception derived from reports by SEALAB aquanauts, Kinney and Cooper (Ref. 20) simulated in the laboratory the homochromatic characteristics of underwater visual environments. Observers adapted during the procedure to constant luminance visual fields of white, blue-green, and (for control purposes) red illumination, and then made judgments on the color appearance of objects displayed within the fields. In a related procedure subjects adapted to each of the three homochromatic fields were then given detection time tests of the colored objects previously used. The amount of change in the appearance of colors was highly significant, ". . . easily accounting for the reports of SEALAB divers who said they could see yellows and reds when there were none present. There was however no change in the subjects' speed of reacting to the colors."

To examine the notion that contextual cues may be related to the visual perception of depth, Luria, Kinney, and Weissman (Ref. 21) performed laboratory experiments investigating the nature of the "filled-unfilled space" illusion. They concluded that, when there was a clear contextual connection between the observer's viewpoint and a "standard" or reference object with which another ("variable") had to be compared, the standard and variable objects appeared to be closer together than when the connection was absent. Observers viewed the test objects with both eyes and one eye at various times; it was concluded that the results of the experiment could not be attributed to stereoscopic visual effects.

Luria (Ref. 22) studied the ability of divers to equate the distances of objects underwater. In the first of three experiments he tested stereoacuity (visual judgment of relative distances of objects) in air and in water, finding that viewing the depth perception apparatus through approximately 16 ft of water degraded stereoacuity by a factor of 4 compared with viewing over the same distance from the surface. In the second experiment, the effect of water clarity on stereoacuity was studied at four levels of light transmissability. It was found that relative depth perception deteriorates as water clarity decreases and that depth perception becomes more variable. A third experiment was run to test the effect of the loss of part of the peripheral field on foveal (central) stereoacuity by reducing the visual angle for each eye to 10° with special goggles; this time the observers viewed the test apparatus in air to isolate the water effect. It was found that restricting the field of view did not produce the overall degradation produced by viewing through water, although observers were about as variable as before. Taking the results of the three experiments together, it was concluded that the loss of stereoacuity underwater is a function of two possibly interacting variables: water clarity and peripheral visual cues.

Weltman, Christianson, and Egstrom (Ref. 23) investigated the effects of five different face masks worn by SCUBA divers on the angular size of the visual field available. They found that all five masks permitted practically full use of the upper field (limited only by divers' eyebrows), but that they all imposed considerable restriction on side visibility; "however, quite a large useful area remained." The three standard partial masks used in the study imposed severe limitation of lower quadrant visibility and are considered by the authors to be detrimental in underwater search tasks or with with equipment at very close range. It was concluded that the full face mask--despite the problem of supplying air without impairing vision--provided the diver with the most effective seeing capability under water. A novel visual perimetry apparatus is described, as developed for use in these experiments.

Andersen (Ref. 24) reports experiments conducted in the Bahamas, in the open ocean, comparing the visual search capabilities of SCUBA divers and submersible vessel operators in locating and identifying targets laid out along a linear course and presented to observers at three viewing distances. The working depth was 55 ft, visibility was 50 ft, and the submersible vessel was operated over the course at three different speeds. The test targets were designed to combine three forms (square, triangle, circle) with five colors (black, red, yellow, blue, and green). Each of three subjects served both as SCUBA diver-observer and as vehicle operator-observer (STAR II was the vehicle used). The conclusion reached was that there were ". . . no significant differences in the ability of SCUBA divers and submersible operators to discriminate color and form or in their visual acuity." The author notes that vehicle operators confused red targets with blue or green, while SCUBA divers consistently confused red with black. From his discussion it appears that Andersen concludes that black and green were also highly confusable under the conditions of his study, but that blue and yellow were easily distinguishable and very accurately identified, regardless of viewing distance.

While not primarily concerned with vision as an independent variable, the experiments of Weltman and Egstrom (Ref. 15) on perceptual narrowing are relevant to a consideration of the effects of the underwater environment on divers' seeing ability. Although their results were anything but strongly conclusive, they contain a suggestion, underscored by the more definitive work of others [see for example MacInnis (Ref. 25)], that heightened levels of anxiety can reduce divers' ability to sense events occurring at or near the edge of their fields of vision while they are concentrating on a fairly demanding task.

c. Tactile

The Mackworth V test has been widely used to measure the effects of water temperature on divers' finger numbness, in terms of tactile discrimination. Bowen and Pepler (Ref. 1) obtained tactile discrimination threshold data on four subjects, first on land then after 12 minutes' exposure to five water temperatures ranging from 70°F downward to 44°F, and found systematic, significant increase in threshold as water temperature decreased. They noted that this probably accounted in part for deterioration of performance underwater where fine dexterity is called for. Stang's results (Ref. 3) agree, in fact showing finger sensitivity deteriorating by better than 50% when divers are subjected to 50°F water temperature for 90 minutes, compared with sensitivity at 70°F for the same length of time. Both Bowen and Pepler, and Stang interpret these findings as explaining divers' difficulty in handling small objects during underwater assembly work; Bowen and Pepler note that their divers reported that, as their fingers became increasingly numb, they had to pay closer visual attention to their work, diverting attention from routine checking of personal equipment and other necessary operations.

Baddeley (Ref. 8) administered the V test to diver subjects on dry land and at two underwater depths in open sea (10 and 100 ft), primarily to assess effects of nitrogen narcosis on tactile sensitivity; he found no significant change in threshold with depth. Water temperatures encountered during his experiments were not reported.

4. Communications

Since relevant literature considered during this project related only to voice communication under actual or simulated underwater conditions, the following review will discuss only that mode. As previously noted in the discussion of auditory perception, the Project SEALAB II report described aquanauts' observations of speech under hyperbaric (200 ft) helium-oxygen atmosphere, but reported no quantitative findings. Most of the available publications originated at the research laboratories of the Navy Submarine Medical Center, located at the Submarine Base, New London, Connecticut.

One of the earliest systematic investigations of the effect of helium-oxygen atmosphere on speech was reported in 1962 by Beil (Ref. 26). He had four male speakers inhale pure medical helium, then repeatedly utter each of six English vowel sounds; for each speaker 12 repetitions under helium and 8 under normal air (for comparison purposes) were recorded for detailed spectral analysis. It was shown that an increase occurred in the component frequencies of each vowel sound, but that the ratios between formants remained nearly constant. Sergeant (Ref. 27) made formal word and sentence list intelligibility measurements on the speech of two male subjects prior to and during a 144-hour helium-oxygen test chamber experiment at atmospheric pressure. He found that during the first 2 days, speech intelligibility deteriorated significantly, but then improved, returning almost to normal by the end of four days; this was interpreted as evidence of an adaptive process in the talker. This finding supports the anecdotal data collected during SEALAB II in which aquanauts stated that they observed adaptation occurring among themselves as their 15-day submergence periods proceeded, specifically mentioning a lowering of voice pitch and slowing down of speaking rate. (Sergeant did not undertake to explain the mechanism of adaptation revealed by his data.)

In a somewhat later paper, Sergeant (Refs. 28, 29) reported the results of intelligibility and acoustic spectrum measurements on the speech of five Navy divers breathing 81% helium-19% oxygen mixture at atmospheric pressure, confirming the earlier finding of decreased intelligibility. He noted that, although voice quality changed drastically, the fundamental voice frequency did not shift appreciably and could be maintained at or near a given level by conscious effort on the part of the speaker. He calculated that the formant frequencies, related to changes in resonant characteristics of the cavities above the vocal folds themselves, shifted upward by an average ratio of 1.51, compared with normal air frequencies.

In an attempt to improve the intelligibility of helium speech, Sergeant (Ref. 30) experimented with a variety of passband filters through which tape recorded samples of helium-oxygen and air speech had been processed. He came to the conclusion that no condition of filtering would increase helium speech intelligibility as compared with the no-filter condition.*

In England, Holywell and Harvey (Ref. 31) made detailed measurements of the fundamental and formant frequencies of speech uttered by speakers breathing air and again helium-oxygen, at both normal atmospheric and four-atmosphere pressures. In addition to confirming Sergeant's formant frequency shift in helium-oxygen of 1.5 times the air frequency at normal pressure, they showed that four atmosphere air produced an upward shift in formant frequencies (compared with normal pressure air), and a slight shift upward in the voice fundamental. This pressure induced shift

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* It is not clear why Sergeant chose to attack the problem of helium-oxygen speech intelligibility restoration in this way because passive filtering, as he employed it, does not counteract the upward frequency shift he had discovered in the experiment discussed previously.

occurred only when air was the breathing gas; helium under four-atmosphere pressure seemed not to produce a greater shift than it did at normal pressure. They further experimented with a simple technique to improve intelligibility of helium speech by restoring it to its original frequencies--playing back tape recordings at reduced speed. An average improvement of almost tenfold was reported.

Brubaker and Wurst (Ref. 32) studied the effects of helium-oxygen at simulated depths down to 300 ft on spectra of speech sounds, generally corroborating Holywell and Harvey with respect to the He-induced formant shifts. Additionally, they noted that at 300 ft, vocal frequencies were 0.5 to 0.6 octave higher than at surface pressure. The authors interpreted this response to indicate increased vocal effort on the part of the speakers in response to the effects of increased pressure on air conduction hearing, and therefore on the speakers' evaluations of their own vocal output.

Gerstman, Gamertsfelder, and Goldberger (Ref. 33) reported the effects on speech formant frequencies of various pressures and compositions of helium-oxygen mixtures, concluding that the relationships were sufficiently complex as to render restoration of original intelligibility by instrumental means complicated and costly, with reasonable approximation the most practical goal. (The paper, incidentally, is an expansion and informalization of a much more compressed presentation given before the Acoustical Society of America at its 72nd meeting in Los Angeles, November 1966.)

More recently, Sergeant (Ref. 34) constructed a confusion matrix for English consonants from experimental data as a first step in establishing a rationale for predicting intelligibilities of special vocabularies that might be designed for use by helium-oxygen-breathing divers. All data were obtained from four speakers breathing 80% helium-20% oxygen at normal atmospheric pressure. It was concluded that ". . . there is a marked similarity between helium speech and speech in air when intelligibility according to linguistic classification is observed. However, unaccountable differences do exist between the two breathing media for ranked intelligibilities of specific consonants."

In a paper given before a recent meeting of the Instrument Society of America, Sergeant (Ref. 35) reviewed the known and probable causes of speech communication distortions in deep diving; this paper presents no original data, but does provide a useful tutorial overview of certain fundamentals of speech production as well as practical considerations imposed by the deep submergence environment (down to 1,000 ft).

In connection with developmental techniques for restoring intelligibility to helium speech at a simulated depth of 400 ft (13 atm), Sargeant (Ref. 36) utilized a "high fidelity" (characteristics otherwise not described) system for tape recording standard intelligibility word lists read by an experienced diver in an atmosphere consisting of 88% helium, 6% nitrogen, and 6% oxygen. When played back at original recording speed (formant frequencies uncorrected for helium shift), 78.0% intelligibility was obtained; when playback speed was reduced to one-half normal speed, intelligibility rose to 96.8%. It was noted that voice quality under this latter technique was quite different, but that distortions were evidently introduced to the detriment of recognition of the speaker's voice. A second technique was tried (the Varivox tape playback, consisting of counterrotating tape transport and pickup head assembly) and yielded intelligibility of 85.6%, which was interpreted by the author as "significant."

In a paper to be published as a chapter in a medically oriented book on diving and performance under hyperbaric atmospheres, Sergeant (Ref. 37) reviews current knowledge regarding speech communication, pressure, and atmospheric composition, and examines the efficacy of several corrective or "speech unscrambling" techniques. This paper makes no attempt to report new findings, but summarizes adequately material compiled from widely disparate sources (Ref. 38).

Appendix B

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Appendix C

REVIEW OF THE PERFORMANCE CAPABILITIES OF MECHANICAL MANIPULATORS

CONTENTS

Appendix C

REVIEW OF THE PERFORMANCE CAPABILITIES OF MECHANICAL MANIPULATORS

A. Underwater Mechanical Manipulator Design Considerations

Present-day mechanical manipulators may be categorized as follows:

- Mechanical master-slave type, which duplicates the motions of the operator's hand by means of a purely mechanical linkage. Feedback is transmitted back through the linkage, and sensitivity of feedback is proportional to the inertia of the system.

- Servomanipulator, or powered master-slave type, which duplicates the motions of the operator's hand by means of proportional control links, either electrical or hydraulic.

- Rate-controlled, powered manipulator type, which is operated by an open-loop control system and actuated by on-off switches with provision for rate control. Feedback is visual only.

The mechanical master-slave is the manipulator used in most nuclear installations. Its virtues are high reliability, ease of use, and good dexterity; feedback is automatically supplied through the mechanical linkage. The servomanipulator has the dexterity and ease of use of the mechanical master-slave and has the benefit of complete mechanical separation of operator and manipulator. Unfortunately, the requirement for feedback control imposes such complexity on the system that this type of manipulator has not yet achieved the degree of reliability desired, even for land operation.

Neither of the above two classes of manipulators appears practical for undersea use. The master-slave concept of the two manipulators requires that the operator have the capability of complete arm swing, which is a space luxury that usually cannot be afforded in the deep submersible. The mechanical master-slave also is infeasible because of the need for penetration of the pressure hull with mechanical linkages, which is difficult at extreme depths. The servomanipulator does not require such hull penetrations, but, as noted above, such manipulators are currently too complex and unreliable for undersea use.

For these reasons, all of the manipulators currently in use in submersible vehicles appear to be either fixed or variable rate-controlled, powered manipulators. Many have small, portable control boxes that may be carried by the operator to the viewport affording the best visual control of the task. Although feedback is primarily visual, suggested aids include a device for indicating the grip force being exerted by the manipulator terminal device and a small hydrophone mounted near the manipulator arm to transmit the sounds of striking small objects. Of course, visual feedback may be obtained directly or by means of periscope or television.

One manipulator arm would seem to suffice for most oceanographic missions, but it appears that two arms are necessary if the submersible is to perform meaningful work. The arms are spot-mounted on the hull, and it appears that the most efficient arm configuration is one resembling the human arm (that is, with universal joints corresponding to the human wrist and shoulder, and another joint corresponding to the human elbow).

It is generally recognized that, to be at all efficient underwater, a work boat must have the capability of exhanging terminal devices on the manipulator arm. Although the choice and design of terminal devices to be carried will depend to a great extent on the particular mission, in general this capability is preferable to using an "all-purpose" terminal device to hold and actuate a separate took, as has been the previous practice. Such a capability allows the tool to be mechanically coupled to a motor with an impact wrench or drill chuck, avoiding the necessity of either using self-powered tools or having trailing electrical or hydraulic connections to the tool.

Some of the considerations that must be taken into account in designing mechanical manipulators for undersea use are as follows:

- Hydrostatic pressure

  As mentioned previously, this factor imposes limitations on pressure hull penetrations and, hence, on mechanical linkages. It also affects the design of hydraulic control lines, which must usually be pressure compensating in some way.

- Corrosion and conduction

  The corroding action of seawater played havoc with some of the early manipulator models, especially affecting fastenings and castings and spots where the surface of the manipulator arm had been scraped. Most manipulators are now being made from stainless steel, but still may suffer from corrosion if left in the water for prolonged periods without maintenance. The high electrical conduction of seawater requires rigid insulation standards for all electrical lines and motors used in the manipulator.

- Visibility

  Frequent conditions of reduced visibility limit the effective lengths of the manipulator arm. A 6-ft arm reach seems to be about the maximum usable under normal conditions, although a 12-ft arm has been recommended for a vehicle that will have to support heavy objects. (However, it was noted that the full 12-ft extension may frequently be of no use because of the poor visibility conditions that can be expected.) Even though visibility may be sufficient to carry out the task, the loss of detail, and especially of perspective, may be sufficient to affect severely the time required for task completion.

- Relative motion

  Excessive motion between the vehicle and the object to be manipulated can make effective manipulation difficult, if not impossible. The vehicle to which the manipulator is attached must supply gross positioning ability, but most vehicles cannot maneuver to the 1/4- or 1/2-in positioning requirements of many remote handling tasks and hence cannot be used for fine positioning. Rather, the vehicle must provide a stable platform, through grappling onto the object to be manipulated, using auxiliary anchoring systems, trim systems, and the like. According to studies conducted at North American Rockwell, the maximum tolerable rate of motion between the outstretched manipulator arm and the object to be manipulated is 4 in/sec.

A 50-lb capacity seems to be the nominal value for manipulator arms on work boats (where capacity is defined as the force that the outstretched arm can exert in any direction). Some manipulators designed for heavy salvage work have capacities up to 500 lb, but a 50-lb capacity is enough to enable the manipulator to handle tools of a size that a man would have to use two arms to support. In general, larger capacity arms carry with them the burdens of increased clumsiness and problems in maintaining a stable platform with the vehicle.

B. Underwater Mechanical Manipulator Characteristics

A comprehensive study of tasks to be performed by five deep submergence vehicles established the required characteristics of mechanical manipulators (Ref. 1). The following vehicles were considered.

1. AUTEC Vehicle

The AUTEC is a relatively small vehicle intended for use with the AUTEC program. It is to be capable of assisting in salvage operations to a depth of 6,500 ft. It also must be able to inspect, test, retrieve, and place electronic systems on the ocean bottom, as well as to perform other oceanographic operations.

2. Deep Submergence Rescue Vehicle (DSRV)

The primary mission of the DSRV is to rescue personnel from disabled submarines. The designs specify operations to a depth of 9,000 ft, with visibility limited to 3 ft. The vehicle is to mate with a disabled submarine and shuttle personnel in groups of 12 to a surface ship or another submarine.

3. Oceanographic Submarine (NR-1)

The NR-1 is a large research submersible capable of extended cruising. Manipulators would be used for such tasks as exploration of the continental shelves and maintenance of equipment, search, and recovery on the ocean floor.

4. TRIESTE III

The TRIESTE III is a bathyscaph similar to TRIESTE II; its primary mission is to reach great ocean depths, to 20,000 ft, and to observe conditions on the ocean floor.

5. Deep Submergence Search Vehicle (DSSV)

The DSSV is designed to operate at cruising speed over fairly large distances, carrying a crew of three to depths of 20,000 ft. It will recover and transport objects weighing up to 150 lb from its design depth and will assist in salvage at depths to 2,000 ft.

The manipulators proposed for vehicles 1, 2, 4, and 5 are identical in specifications; the manipulator proposed for vehicle 3 is essentially a larger version of the same manipulator. In the following summary, specifications are given for the smaller manipulator, with specifications for the large manipulator of vehicle 3 shown in parentheses if they differ.

- Reach

  Minimum active length, 72 in (144 in).
  Maximum retracted length, 36 in (72 in).

- Capacity

  Minimum wrist-roll torque, 1,500 in/lb (10,000 in/lb).
  Minimum force exertable in any direction, 50 lb (250 lb).
  The small manipulator should also be able to exert a 600-lb force in the horizontal direction 3 ft below the shoulder axis.

- Degree of freedom

  Each manipulator should have seven degrees of freedom, each controlled by a separate actuator. There is to be no visible backlash, nor any visible overshoot resulting from the motion of starting or stopping the manipulator.

- Motion rates

  Range of shoulder vertical, horizontal, and elbow motion, 1/2 in/sec to 8 in/sec.
  Range of wrist vertical, horizontal, and extend motion, 1/4 in/sec to 4 in/sec.
  Range of wrist rotate motion, 1/2 rpm to 8 rpm.

- Motion locking

  Each of the above motions should hold its position when the manipulator is not in action. Tolerated motion drift is not to exceed 1/16 in/min with full rated load (cumulative over all motions).

- High force terminal device actuator

  Maximum grip force provided, 2,000 lb through 4-in stroke (8,000 lb through 8-in stroke).
  Range of controllable grip force, 100-2,000 lb (400-8,000 lb).
  Accuracy of controllable grip force, ±20%.

- High speed terminal device actuator

  Range of drive speed, 400-3,450 rpm.
  Maximum torque, 30 in/lb (300 in/lb).

The following terminal devices may be positioned at the end of the manipulator and actuated by one of the terminal device actuators:

- Hook hand

  Jaws shaped to fit hexogonal stock and close to zero opening at the center of the grip.
  Maximum grip force, 2,000 lb (8,000 lb).
  Maximum opening, 2-1/4 in (5 in).
  Stroke, 4 in (8 in).

- Parallel jaw hand

  Closes to zero opening; application of full-wrist torque will not permanently distort jaw mechanism.
  Maximum grip force, 1,500 lb (3,000 lb).
  Maximum opening, 5 in (10 in).

- Three-jaw clam shell gripper

  Formed by three orange peel jaws.
  Maximum diameter of object encompassed, 12 in (16 in).
  Minimum gap between section when closed, 1/16 in.

- Prosthetic hand

  Patterned after the split prosthetic hook design.
  Maximum diameter of object grasped, 5 in (10 in).
  Maximum grip force at knee of hook, 250 lb (1,000 lb).

- Grapple hand

  In planar movement, 2 tines interleave with 1 opposing tine.
  Range of diameters gripped firmly, 0 to 12 in.
  Maximum grip force, 250 lb (1,000 lb).

- Drill chuck

  Of the standard Jacobs design, but equipped with rotation stops in the outer sleeve.
  Capacity, 0 to 1/2 in (0 to 1 in).

- Centrifugal pump

  Used either as suction or jetting device, with nozzles exchanged by divers. The pump should be driven by a high speed terminal device actuator.

- Impact head

  Modification of standard square drive, continuous rotation input type of impact wrench, using the head portion only and relying on the high speed terminal device for actuation. Head size, 1/2-in-square (1-in-square).

- Cable cutter

  Capable of shearing a limp stainless steel cable. Maximum diameter of cable to be cut, 1 in (2 in).

- Stud gun

  Thickness of plate to be penetrated, 1/2 in. Maximum shear or extraction strength of stud, 4,000 lb.

The following remarks are general conclusions reached in the study bearing on the above specifications:

- Since weight is generally a critical factor, the smallest possible manipulator is desirable. About a 6-ft reach is the minimum length to allow reasonable area coverage by the manipulator, and the 6-ft long, 50-lb capacity arm is consistent with the mission and viewing requirements of the smaller vehicles. The size of the arm for the NR-1 is consistent with vehicle size and mission, although it should be noted that vision may be poor for this large an arm in turbid water.

- In general, manipulators should not be used as cranes or heavy-weight lifters, but rather as "riggers." Many manually operated tools can be modified for use with manipulators. A 50-lb manipulator capacity (which is compatible with the 6-ft size manipulator) will be adequate for handling power tools of the type that are normally hand-held and have been modified for underwater use.

- It should be noted that load capacities are specified for the worst arm configurations and that up to double this specified capacity may be handled in more favorable manipulator positions.

- At least six degrees of freedom are required if the manipulator is to have full capability of locating and orienting the terminal device. A seventh degree of freedom, wrist extension, is included to speed up many of the manipulator operations.

C. Capabilities of Underwater Mechanical Manipulators

The most satisfactory applications for underwater mechanical manipulators will probably be related to construction, assembly, or maintenance since these tasks can be specifically engineered and designed to accommodate the shortcomings of mechanical manipulations. Such design considerations should include the following:

- Providing easy access to all nuts, bolts, valves, and the like
- Minimizing the number of different nut sizes
- Fitting all nuts with conical heads
- Redesigning clamps and other hardware requiring "two-handed" operation
- Utilizing nonjammable threads and large access holes in nuts and trapped holes
- Making nuts and bolts captive so they will not be dropped.

Manipulators may be less useful in nondesignable jobs, such as salvage tasks, where the limited versatility of manipulator tools may be inadequate for the job. However, given enough time, even these jobs can be accomplished by mechanical manipulation with the limits of dexterity and mobility imposed by the vehicle manipulator system.

The question of how much more time it will take a manipulator to perform a given task compared with the time required for manual performance is still a matter of conjecture. R. C. Goertz, in "Human Factors in Design of Remote Handling Equipment," notes that on dry land a mechanical master-slave manipulator takes 6 to 10 times as long as a man to perform a given task, and as much as 10 times as long for a rate-controlled manipulator compared with a master-slave. Therefore, under shirtsleeve conditions, an undersea manipulator might be as much as

100 times slower than a man in performing a task. However, in the underwater environment, this ratio decreases to a factor of about 10 when compared with a shallow-depth SCUBA diver, and equals, and finally surpasses, a hard-hat diver at his marginal depths.

Unfortunately, actual experience in underwater mechanical manipulation at present is so limited that the above remarks can be considered to be only educated guesses. It appears that this question will be partly answered by the performance of the BEAVER MARK IV vehicle, to be launched soon by North American Rockwell. Since the BEAVER is the first submersible to be designed as a work boat from the keel up, the performance of this vehicle in actual underwater tasks will yield a state-of-the-art comparison between the underwater capabilities of man and those of mechanical manipulators. So far, no information on the performance of the BEAVER manipulator is available, but several facts seem fairly evident from the brief view of the vehicle and of a film clip of manipulator tests:

- The manipulator movements are rate-controlled by the operator, but it is not known which controls the operator uses to control the manipulator or what feedback considerations may have been added to supplement those obtained visually.

- Fine positioning capability of the manipulator arm, as shown in the demonstration film, seemed limited effectively to motions on the order of 1 to 1/2 in, with overall manipulative capability generally quite clumsy. Although satisfactory alignment of such tools as drill chucks, stud guns, and impact wrenches may simply be a matter of taking enough time, the manipulator seems unsuited for work requiring any appreciable degree of "dexterity." Complicated patterns of wrist movement appear to be extremely time consuming to perform with the manipulator, and, of course, the manipulator is totally incapable of "finger work," i.e., those tasks involving such small and precise movements that a human could perform them with his fingers with wrist fixed.

- The operators of the manipulator seem to have much trouble with perspective and with the orientation of the terminal device in the desired geometrical relationship with the object to be worked on. For example, in using a stud gun the operator had great difficulty in placing the gun perpendicular to the surface, sometimes being in error by as much as 30 degrees.

In summary, all signs seem to indicate that current undersea mechanical manipulators may minimize the need for man, but they certainly cannot replace him. The manipulators are built on too gross a scale to accomplish jobs requiring fine dexterity or precision, so at least for the present man must be available to accomplish such jobs. Although the manipulators will probably outperform man in tasks requiring the use of the powered terminal devices, such as the impact wrench, we have yet to see whether manipulators will be capable of using the general purpose hands to effectively use other hand tools that may occasionally be needed.

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Appendix D

COST DATA SUMMARY

ILLUSTRATIONS

TABLES

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Appendix D

COST DATA SUMMARY

The procurement and operating costs of undersea work and support systems used in the study were gathered from four principal sources, viz.:

1. The Large Object Salvage System (LOSS) study*
2. The draft of a proposed technical approach developed by the Naval facilities Engineering Command
3. Open literature publications, including Undersea Technology and Ocean Industry
4. Estimates provided during discussions held between the study team and persons concerned with undersea systems development.

In keeping with the subjective nature of the study, and in the absence of precise fiscal data, the cost comparisons of alternative work systems were accomplished on an order-of-magnitude basis. The surface support ship costs, MAN-IN-THE-SEA system costs, and the costs of alternatives to MAN-IN-THE-SEA systems used in the study are summarized in the following figures and tables.

Figure D-1 summarizes the procurement costs of surface support ships in terms of total ship displacement.

Figure D-2 summarizes the operating costs of surface support ships in terms of total ship displacement.

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* "Large Object Salvage Study," Vols. I and II; General Dynamics Corporation, Electric Boat Division, Groton Conn.; prepared for Navy Special Projects Office, Contract NOsp 65185-C; 30 September 1965 (UNCLASSIFIED).

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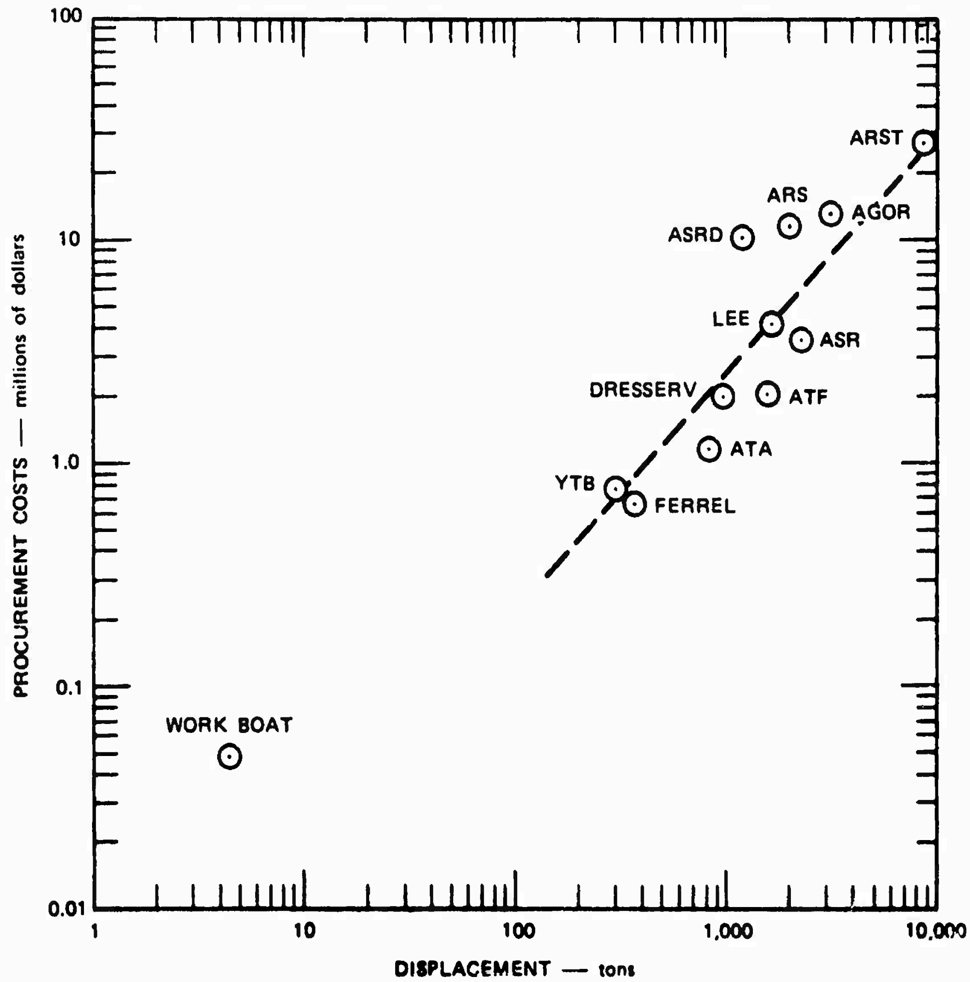

FIGURE D-1 PROCUREMENT COSTS OF SURFACE SUPPORT SHIPS

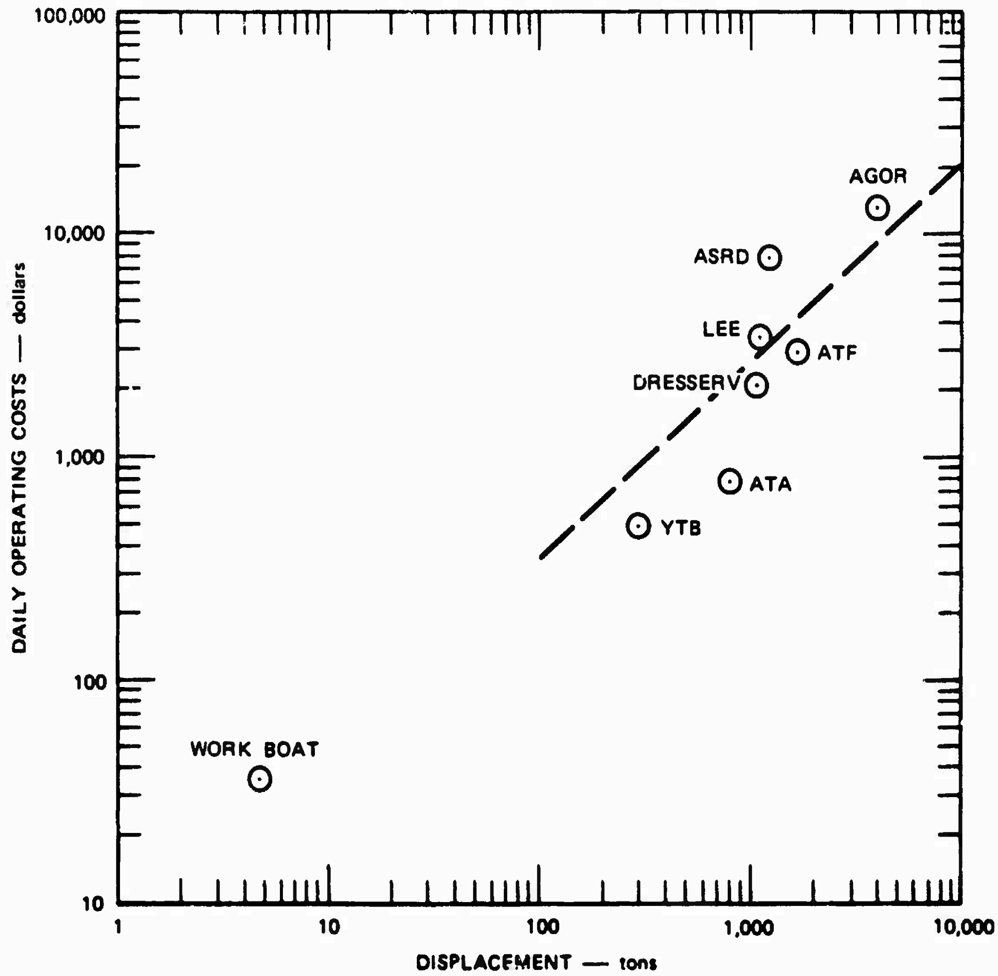

FIGURE D-2 OPERATING COSTS OF SURFACE SUPPORT SHIPS

Table D-1 summarizes the procurement and operating costs of MAN-IN-THE-SEA systems in terms of the applicable depth regime. The cost of a combined system is made up of the cost of personnel life support components and operational life support components. The latter comprises decompression facilities, personnel transfer capsule, personnel transfer vehicle, or a habitat.

Table D-2 summarizes the procurement and operating costs of alternative systems to MAN-IN-THE-SEA. The system options include the manned free vehicles, the manned tethered vehicle, and the unmanned tethered vehicle.

Table D-1

PROCUREMENT AND OPERATING COST ESTIMATE FOR MAN-IN-THE-SEA SYSTEMS

MAN-IN-THE-SEA Systems Options			Operational Life Support Components								Personnel Life Support Components	
Category	Applicable Depth Regime	Breathing Mixture	Decompression Facilities P	Decompression Facilities O	Personnel Transfer Capsule (PTC) P	Personnel Transfer Capsule (PTC) O	Personnel Transfer Vehicle (PTV) P	Personnel Transfer Vehicle (PTV) O	Habitat P	Habitat O	P $/man	O $/man-day
Direct Surface Supported System	0-30 ft	Air									$1,000 / 500	$<10
	30-150 ft	Air	$3,000* / 2,000	$<10							$1,000 / 500	$<10
	150-300 ft	Mixed $He-N_2-O_2$	$2,000,000 / 1,000,000	$200 / 100							$5,000 / 3,000	$30 / 20
Augmented Surface Supported System (PTC)	300 ft	Mixed $He-N_2-O_2$	↓	↓	$500,000 / 300,000	$200 / 100					↓	↓
	300 ft	Mixed $He-N_2-O_2$	↓	↓	↓	↓			$1,000,000 / 500,000	$500 / 250	↓	↓
Augmented Surface Supported System (PTV)	300 ft	Mixed $He-N_2-O_2$	↓	↓			$1,000,000 / 500,000	$1,500 / 1,000			↓	↓
	300 ft	Mixed $He-N_2-O_2$	↓	↓			↓	↓	$1,000,000 / 500,000	$500 / 250	↓	↓
Self Contained Mobile Habitat		Mixed $He-N_2-O_2$									↓	↓

P -- Procurement cost.

O -- Operating cost ($/day).

* -- High cost estimate / Low cost estimate

** -- Surface support vessel displacement.

Table D-2

PROCUREMENT AND OPERATING COST ESTIMATE FOR ALTERNATIVE SYSTEMS TO MAN-IN-THE-SEA

System Options		Vehicle Cost	
Category	Examples	Procurement	Operating ($/day)
Manned free vehicles	ALVIN AUTEC BEAVER	$1,000,000* 500,000	$1,500 1,000
Manned tethered vehicle	ARTICULATE DIVING DRESS (300 ft max)	$ 20,000 10,000	$ 200 100
	GUPPY	$ 200,000 150,000	$1,000 500
Unmanned tethered vehicle	CURV	$1,000,000 500,000	$ 500 250

* High cost estimate
Low cost estimate

Appendix E

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Appendix E

BIBLIOGRAPHY

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13. ABSTRACT

Naval undersea missions and operations in the 1975-85 time frame that require the use of MAN-IN-THE-SEA systems are delineated. The MAN-IN-THE-SEA system is broadly defined in this study to include all undersea systems requiring man's exposure to the ambient ocean pressure. MAN-IN-THE-SEA missions and operations within the overall spectrum of naval undersea missions and operations are isolated on the basis of system investment and operating costs. It is demonstrated that MAN-IN-THE-SEA has a definite role in accomplishing future naval undersea missions and operations. MAN-IN-THE-SEA systems offer both functional and cost advantages over alternative systems in the performance of a number of naval missions in the shallower depth regions (less than 150 feet). In depths greater than 150 feet, MAN-IN-THE-SEA systems offer functional advantages at comparable costs to alternative systems in the performance of some naval missions.

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Recovery						
Reconnaissance						
Underwater Construction						
Habitat						
Functional Comparison						
Cost Comparison						